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Routing, Modulation and Spectrum Assignment Algorithm Using Multi-Path Routing and Best-Fit

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ABSTRACT Elastic Optical Networks (EONs) are a promising optical technology to deal with the ever-increasing traffic and the vast number of connected devices of the next generation of the Internet, associated to paradigms like the Internet of Things (IoT), the Tactile Internet or the Industry 4.0, to name just a few. In this kind of optical network, each optical circuit or lightpath is provisioned by means of superchannels of variable bandwidth. In this manner, only the necessary bandwidth to accommodate the demand is allocated, improving the spectrum usage. When establishing a connection, the EON control layer determines the modulation format to be used and allocates a portion of the spectrum in a sequence of fibers from the source to the destination node providing the user-demanded bandwidth. This is known as the routing, modulation level and spectrum assignment (RMSA) problem. In this work, we firstly review the most important contributions in that area, and then, we propose a novel RMSA algorithm, multi-path best-fit (MP-BF), which uses a split spectrum multi-path strategy together with a spectrum assignment technique (best-fit), and which jointly exploit the flexibility of EONs. A simulation study has been conducted comparing the performance of EONs when using MP-BF with other proposals from the literature. The results of this study show that, by using MP-BF, the network can increase its performance in terms of lightpath request blocking ratio and supported traffic load, without affecting the energy per bit or the computation time required to find a solution.

INDEX TERMS EON, RMSA, best-fit, split spectrum, multi-path, survey.

I. INTRODUCTION

Future Internet will have to deal with new applications from many different verticals associated to machine-to-machine (M2M) and human-to-machine (H2M) services that current networks cannot satisfy. The key performance indicators (KPI) required for those applications, the ever-increasing traffic, and the number of connected devices impose stringent requirements to communication networks [1]. While most of the fronthaul networks will be based on multi-radio access technologies (RAT), the backhaul will be built over optical networks due to their high capacity, flexibility and adaptability [2].

Wavelength-routed optical networks (WRONs) use wavelength division multiplexing (WDM) techniques to increase the capacity of the links. However, the wavelengths have an additional role, as they are also used for routing purposes, hence the name of this type of networks. WRONs are based on the establishment of optical circuits, called lightpaths, between two network nodes that do not need to be adjacent in the network topology. The establishment of these lightpaths implies the reservation of a wavelength over a sequence of fibers from the source to the destination node (path or route). Therefore, the control plane of those networks must solve the routing and wavelength assignment (RWA) problem.

WRONs use fixed ITU-T channels (typically, of 50 GHz bandwidth) to set up lightpaths. To make a most efficient use of the capacity of fibers, single line rate WRONs migrated towards mixed line rate solutions in which multiple line rates coexist in the same network but still using ITU-T fixed channels. Nevertheless, the use of techniques like orthogonal frequency division multiplexing (OFDM)

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or Nyquist-WDM [3], [4], in conjunction with the development of devices like the bandwidth-variable transponder (BVT) and the bandwidth-variable optical cross-connect (BV-OXC) [5] favored the appearance of flexible network architectures like spectrum-sliced elastic optical path network (SLICE) [6]. The main characteristic of these elastic optical networks (EONs) is the possibility of allocating a variable portion of spectrum to each connection adjusted to the actual traffic demand. Therefore, the traffic is transported in multiple low-rate subcarriers, providing sub-wavelength granularity for low traffic requests, or superchannels to transport high-rate demands, making more efficient use of the spectrum.

In EONs, the RWA problem becomes the routing and spectrum assignment (RSA) problem [7]. Therefore, to set up a new lightpath, the control layer must assign a portion of spectrum (rather than a single wavelength) along a sequence of fibers from the source to the destination node (route) that satisfies the user request. To avoid interference between lightpaths, a guard-band between contiguous channels is typically introduced. There are several studies in the literature that address the RSA problem, either considering the spectrum as a continuous block that can be assigned in slices (gridless) [8]–[10], or dividing the spectrum in narrow frequency slots (FSs) of fixed width and allocating enough consecutive slots to a request to satisfy the demanded traffic along the fibers that compose the allocated route (flexgrid) [5], [11], [12].

On the other hand, to avoid request blocking due to the lack of enough consecutive spectrum to support the demanded traffic, split spectrum techniques can be applied [13]–[15]. These techniques allow providing the total requested capacity through multiple connections of smaller capacity (which will be referred to as sub-lightpaths from now on) and routing them either through the same path (single-path approach) or different paths (multi-path approach).

As most EONs are equipped with multi-rate/multi-format transceivers, the RSA problem can be extended to incorporate the selection of the modulation format, turning into the routing, modulation level and spectrum assignment (RMSA) problem. This kind of algorithm selects the most efficient modulation scheme, in terms of spectral efficiency, that can be used in a route with acceptable quality of transmission (QoT). More efficient modulation formats reduce the symbol rate while maintaining the transmission rate, hence requiring less spectrum to satisfy the traffic demand [16]. The performance of the modulation formats is impacted by inter-symbol interference, inter-channel interference, attenuation, noise and other factors, hence limiting the optical reach of the transmitted signal [16], [17]. For this reason, higher-order modulation formats can be applied to shorter paths compared to lower-order modulation formats. This is also known as distance-adaptive spectrum allocation [16], [18].

In [19], we evaluated the use of a well-known RWA method, k-shortest paths and first-fit, to solve the dynamic RSA problem considering different levels of flexibility, that is, we studied the advantages of employing gridless spectrum and the introduction of the sub-lightpath approach. Results from that study show that incrementing the flexibility of the network does not necessarily imply an improvement of the performance of the network, unless using RSA techniques specifically designed to exploit the flexibility of EONs.

The contribution of this paper is twofold. We firstly present a comprehensive review of RSA and RMSA methods. Then, and as the main contribution, we present a new RMSA algorithm for dynamic EONs, multi-path best-fit (MP-BF), which combines the use of a split spectrum multi-path strategy with a spectrum assignment technique called best-fit [20], [21]. Previous studies on the use of best-fit had only considered single-path routing strategies, and had concluded that its performance was similar to that of the well-known first-fit technique [20], [21]. However, in this article we demonstrate that when best-fit is combined with a multi-path strategy, its full potential is realized. Thus, by means of a simulation study, we show that MP-BF outperforms other techniques in terms of connection blocking ratio and supported traffic load, without increasing the network energy consumption or the computation time.

The rest of the paper is structured as follows. In Section II, a survey of the main proposals to solve the RSA/RMSA problems is presented. Section III describes the RMSA algorithm proposed in this paper, MP-BF. Section IV reports the performance comparison of MP-BF with other proposals in terms of different metrics. Lastly, Section V summarizes the main conclusions of the paper.

II. RELATED WORK

A. STATIC RSA AND RMSA

In static EONs, where the traffic demands are known in advance, the RSA problem consists in allocating a route (i.e., a sequence of fibers from the source to the destination node) and a portion of spectrum that satisfies the bandwidth requirements of all the demands. That problem can be solved using mathematical formulations or by means of heuristics, some of them based on artificial intelligence techniques.

There are several proposals which use mathematical formulations to solve the RSA/RMSA problem (Table 1). For instance, Klinkowsky and Walkowiak [12] proposed an integer linear programming (ILP) formulation that solves the RSA problem minimizing the number of occupied FSs. Christodoulopoulos *et al.* proposed in [3] and [4] various ILPs to jointly and separately address the RSA and the RMSA problems. In [3], authors proposed an ILP formulation that jointly solves the routing and the spectrum allocation subproblems to minimize the starting FS index and the number of utilized slots. Moreover, [3] also includes two ILPs to solve first the routing (with the objective of minimizing the cost of routing, computed as the sum of occupied FS along the links that compose the route), and then the spectrum allocation problem (minimizing the maximum used FS). The method is extended in [4] to solve the RMSA problem. The joint RMSA ILP formulation pre-calculates k-shortest paths between each pair of source-destination nodes and selects the route and portion of spectrum that minimizes the routing cost and the starting FS index, considering that the number of required slots will vary according to the selected modulation format, since each modulation scheme has a different maximum length with an acceptable QoT. Furthermore, the paper also solves the separate RMSA by means of an ILP that selects the route and modulation scheme that minimizes the sum of the capacity that the request would occupy in all the links along the route and solving the spectrum assignment following the same procedure proposed in the joint RMSA algorithm. Wang *et al.* [22] proposed an ILP formulation that solves the problem with the aim of minimizing the maximum subcarrier index occupied and the total allocated subcarriers over the fibers of the network. Cai *et al.* [23] solved the joint RSA problem through an ILP formulation that minimizes the maximum FS index employed in the network. Miyagawa *et al.* [24] proposed two ILP models for intra-data center static EONs, aimed at minimizing the number of utilized FSs and maximizing the served traffic requests under a given number of FSs, respectively. Gong *et al.* [25] presented two ILP formulations to solve the RMSA problem with multicast traffic, one optimizing the requests jointly and the other one optimizing each request separately, with the objective of minimizing the maximum employed FS index. Goscien *et al.* [26] proposed two ILP algorithms to solve the joint RMSA problem minimizing the cost and power consumption, and the spectral utilization, respectively. Finally, Zhao *et al.* [27] solved the joint RMSA problem by means of an ILP formulation that minimizes the maximum index of the allocated FS considering non-linear impairments. Behera *et al.* [28] addressed the bit loading problem, i.e., the independent modulation of each FS so that each one is loaded with a different number of bits per subcarrier. Authors proposed a mixed integer linear programming (MILP) formulation to solve the routing, bit loading and spectrum allocation (RBLSA) that selects the route, the spectrum and the modulation level for each allocated FS that minimizes the sum of highest indexed FSs so that the signal-to-interference-plus-noise ratio (SINR) is satisfied. These proposals are summarized in Table 1.

TABLE 1. Mathematical formulations that solve the static RSA and RMSA problems.

Authors	Solving Strategy	Technique	Objective
Klinkowsky and Walkowiak [12]	Joint RSA	ILP	Minimizes the allocated FSs
Christodoulopoulos *et al.* [3], [4].	Joint and separate RSA and RMSA	ILPs	Minimize used spectrum
Wang *et al.* [22]	Joint RSA	ILP	Minimizes maximum FS index and allocated FSs along the fibers of the network
Cai et al. [23]	Joint RSA	ILP	Minimizes maximum FS index employed in the network
Miyagawa *et al.* [24]	Joint RSA	ILP	Two objectives: Minimizes utilized FSs Maximizes number of served connection requests
Gong *et al.* [25]	Joint RMSA	ILPs	Minimize the maximum allocated FS index optimizing connection requests either jointly or separately
Goscien *et al.* [26]	Joint RMSA	ILPs	Minimize the cost and power consumption. Minimize the spectral utilization
Zhao *et al.* [27]	Joint RMSA	ILP	Minimize maximum index of assigned FSs. Considers non-linear impairments
Behera *et al.* [28]	RBLSA	MILP	Minimize maximum index of assigned FSs

RSA/RMSA problems have been shown to be NP-Hard [4], [7], [29]. To overcome this issue, some works have proposed heuristics for solving those problems. Klinkowsky and Walkowiak [12] included in their study a heuristic which solves the problem minimizing the maximum FS index occupied in the network. The proposal processes each demand in decreasing order of demanded FSs, examines all the candidate paths for each demand and selects the one that presents a set of free FSs that satisfy the demand and whose initial FS index is the smallest between all the initial FS indexes of the candidate paths. Cai *et al.* [23] proposed a greedy algorithm that allocates to each traffic demand the shortest path in number of hops that contains the set of free FSs with the lowest index that satisfies the traffic demand. Wang *et al.* [22] proposed two heuristics with the objective of minimizing the maximum subcarrier index. The first one sorts the requests in decreasing order of demanded FSs and, for each request, allocates the shortest path and the set of available FSs with the lowest index. The second heuristic first precomputes k-shortest paths for each pair of source-destination nodes, checks which of the calculated paths minimizes the maximum fiber load and allocates that path and the lowest-indexed set of available FSs. Christodoulopoulos *et al.* [4] accompanied their ILP formulation with a heuristic in which the candidate paths between each pair source-destination are computed, and a greedy algorithm is applied to select the path containing the set of free FSs with the lowest starting index. Gong *et al.* [25] proposed a genetic algorithm that solves the joint RMSA problem minimizing the maximum index of the allocated subcarriers. Goscien *et al.* [26] devised a greedy algorithm that sorts requests in decreasing order of demanded traffic, computes the k-shortest paths between source and destination and allocates to each demand the feasible path that minimizes the cost. The proposal also includes a tabu search that optimizes the solutions obtained with the greedy algorithm by either changing the path, the modulation format or the server when traffic is anycast. Zhao *et al.* [27] also presented a heuristic that calculates k-shortest paths between each pair of source-destination nodes, sorts the requests according to a given criterion and, for each path, modulation format and set of available FSs, computes the cost of each link in the path, assigning the one with the lowest cost. Behera *et al.* [28] proposed a heuristic that sorts the requests according to a certain criterion and solves the RBSA for each request. For that aim, it creates the set of candidate routes computing k-shortest paths and checks each available FS and modulation format to verify if there are enough consecutive available FSs that meet the traffic and the SINR requirements. The algorithm allocates the path with the lowest sum of highest FS indexes in the links. Lastly, Yu *et al.* [30] proposed a heuristic that computes k-shortest paths, sorts the requests utilizing different policies and assigns the first available portion of spectrum that satisfies the demand. These heuristics are summarized in Table 2.

TABLE 2. Heuristics that solve the static RSA and RMSA problems.

Authors	Solving Strategy	Technique	Objective
Klinkowsky and Walkowiak [12]	Joint RSA	Candidate paths calculation and and selection of path with lowest indexed FS	Minimizes the allocated FSs
Cai *et al.* [23]	Joint RSA	Greedy Algorithm	Minimizes maximum FS index
Wang *et al.* [22]	Joint RMSA	Shortest Path + Spectrum reuse and balanced load spectrum allocation	Minimize the maximum allocated FS index
Christodoulopoulos *et al.* [4]	Joint RMSA	Greedy Algorithm	Minimize starting FS index
Gong *et al.* [25]	Joint RMSA	Genetic algorithm	Minimize maximum FS index
Goscien *et al.* [26]	R + SA	k-shortest paths + tabu search	Minimize the cost
Zhao *et al.* [27]	RM + SA	k-shortest paths and modulation + spectrum allocation	Minimize the cost
Behera *et al.* [28]	R + BSA	k-shortest paths + spectrum and modulation allocation	Minimize the allocated FS indexes.
Yu *et al.* [30]	R + SA	k-shortest paths + sorting + first-fit	Minimize the spectrum utilization

B. DYNAMIC RSA AND RMSA

The former studies addressed the RSA and RMSA problems in static EONs. However, a next step in the evolution of EONs is the establishment and release of lightpaths on demand. That scenario is known as the dynamic scenario and, in it, the network control layer must provision user demands with a route and a portion of spectrum that fulfill the user request in a short period of time, as they have to be established in real time. Mathematical formulations are not particularly suitable to dynamic EONs due to the huge computing time that they require. For this reason, it is common to find proposals based on heuristics and meta-heuristics to solve the dynamic RSA/RMSA problems.

The problems can be solved jointly or separately. For example, Wan *et al.* [9] solved the RMSA problem using two strategies for modulation format selection: fixed or adaptive modulation. In the first one, the modulation level is selected at the beginning of the procedure and remains fixed until the RSA problem is solved. In the second strategy, the algorithm selects the most efficient modulation level and tries to solve the RSA problem. If no feasible path is found, the algorithm selects the second most efficient level and tries again. The procedure is repeated until a path is found or until all the modulation schemes are checked. Furthermore, the authors propose two heuristics to solve the RSA problem. The first heuristic builds a decision tree containing all candidate paths with enough available spectrum. The algorithm examines each path, taking as the root the source node and taking as the leaves the adjacent nodes connected with links with sufficient spectrum to satisfy the demand, including the guard-band. At each loop, the algorithm checks the nodes at one hop of each leave. If there are enough available spectrum in the connected link, they are added to the decision tree and the algorithm repeats the procedure with the following hop in the path, until arriving at the destination node. Finally, the algorithm selects the path with enough free FSs and minimum routing cost. Authors also proposed a modified version of Dijkstra's shortest path that computes the shortest path between the source and destination node and the aggregated available spectrum along the path. In this manner, the algorithm verifies if the same consecutive FSs are available in all the links composing the path and if they satisfy the traffic demand, including the required guard-band. Salani *et al.* [31] proposed an ILP formulation to solve the joint RSA problem minimizing the number of transceivers and the occupied spectrum. The formulation is extended to include multiple modulations by adding reach constraints. Furthermore, the ILP is enhanced with machine learning techniques to include a QoT estimation in the solution. Leiva *et al.* [32] solved the RSA problem by means of a dynamic graph coloring algorithm. The algorithm checks each FS in the spectrum and builds sub-graphs that include the links with enough available spectrum to satisfy the demand, assuming that the first FS in the set is the FS being checked. Once all the sub-graphs are built, the algorithm looks for the shortest path in terms of number of hops and assigns the path and the available FSs. Velinska *et al.* [33] adapted the genetic algorithm that solves the RWA problem proposed by Bisbal *et al.* [34] to solve the RMSA problem. The algorithm creates an initial population of random routes that connect the source and destination node of the request, applies classical genetic operations like crossover and mutation and calculates the number of FSs required to satisfy the demanded traffic (that depends on the modulation format that can be applied to the route) and the number of hops. The algorithm returns the best-found route in terms of number of allocated FSs and hops after a number of iterations. Alyatama [35] presented an RSA algorithm that checks all the possible routes between the source and destination nodes and calculates the relative cost of carrying the requested traffic along the route, computed as the difference in the lost revenues when a connection is accepted or not. This relative cost is calculated for all the available sets of FSs in the route. At the end of the process, the algorithm returns the route and the starting FS index that minimizes the relative cost.

The dynamic RSA/RMSA problem can also be solved by separately addressing the routing, the modulation, and the spectrum allocation. The routing problem can be addressed using analogous algorithms to those employed to solve the RWA problem. Hence, well-known techniques like fixed routing (FR) and fixed alternate routing (FAR) can be used. FR has a single pre-calculated route for each source-destination pair of nodes, which is always used. In contrast, FAR has several pre-calculated routes for each source-destination pair of nodes and, upon a lightpath request arrival, each path is checked until finding one with enough idle spectrum. These techniques are employed in [36], where authors also proposed a k-distance adaptive path selection algorithm that pre-computes the candidate paths and required spectrum when the most efficient modulation format (depending on the path) is employed, and selects the path using either FR or FAR. Jinno *et al.* [18] also used a FAR approach to solve the RMSA problem and studied the advantages of selecting the modulation format in terms of spectrum resource utilization. Ahmed *et al.* [37] proposed an RMSA algorithm for coexisting fixed/flexgrid networks, which computes k-shortest paths and selects the one with the highest spectral efficiency, i.e., the one that requires the least bandwidth to serve the requested traffic. Calderón *et al.* [38] proposed a bit error rate (BER)-adaptive RMSA algorithm that computes k-shortest paths and finds the route, the modulation level and the portion of spectrum that meets the traffic requirements with the lowest BER. If the algorithm cannot find a route, set of FSs and a modulation scheme, it splits the route in two segments introducing a regenerating device, and aims at finding a portion of spectrum and a modulation level at each segment independently, so that the BER threshold is met. Alyatama *et al.* [39] employed adaptive routing (AR), in which the routes are calculated according to the network state at the connection request arrival time, to solve the RSA problem. Solutions implementing least congested routing (LCR) can also be found in literature. In this case, the algorithm selects the path with more FSs available among a set of predetermined routes between the source and destination nodes. This method is presented in [2] and employed in [7]. Moreover, Sambo *et al.* [40] used a variation called least congested routing conditioned to modulation format, that calculates the congestion according to the best performing modulation scheme in terms of QoT and spectral efficiency that can be employed in the path. Yuan *et al.* [41] proposed an RMSA algorithm that uses FAR to precompute the list of candidate paths and then selects the route and the consecutive FSs that minimize the available spectrum resource reduction both in the candidate path and in the routes with shared links.

Lastly, the spectrum assignment subproblem can be solved using techniques like the following ones:

(1) First-fit (FF): This scheme indexes the FSs and maintains updated information on the available and occupied FSs. Then, it searches for a set of contiguous FSs that satisfies the traffic demand, in ascending index order, hence allocating the first set of FSs that are available. This tactic is employed in [18], [36], [38], [42], [43] and [44].

(2) Last-fit (LF): This technique works in a similar manner to FF but attempting at allocating the highest indexed FSs to a connection [2].

(3) Random-fit (RF): The algorithm randomly selects the spectrum slices among a list of available FSs, so that the FSs are the same in all the links conforming the first found path and satisfy the demanded traffic [43].

(4) Lowest starting slot (LSS): This method aims at allocating the first set of available FSs that satisfy the traffic demand in any path. Hence, the algorithm checks all the candidate paths between the source and destination nodes and the available slots in increasing index order. Finally, it assigns the path with the lowest-indexed slots [4].

(5) Exact-fit (EF): The algorithm starts to check all the sets of contiguous FSs in increasing index order and allocates the set that exactly matches the requested traffic. If no set fulfills this requirement, the policy allocates FSs using the FF technique [43].

(6) First-last-fit (FLF): This technique partitions incoming requests and, depending on the partition, aims at allocating the available FS either with the lowest or the highest index [45]. Li and Li [46] use this technique in their RSA proposal, which aims at minimizing the utilized spectrum resources and the distance between the candidate FS and a certain boundary.

(7) First-last-exact-fit (FLEF): This spectrum allocation technique [47] classifies connections into non-disjoint and disjoint path requests. The requests with disjoint paths are solved using First-Exact Fit (FEF), which tries to allocate the first set of FSs that exactly adapt to the demanded traffic, or the lowest indexed FSs that satisfies the demand, if not exact fit is found. On the other hand, the connections with non-disjoint paths are solved using Last-exact Fit (LEF), that performs analogously to FEF but starting the search at the highest-indexed FSs.

(8) Reusable spectrum allocation first (RSAF): This technique classifies slots into two categories: slots that have been allocated to previous connections (and released once the connection is torn down) and slots that have never been allocated to a connection. When a connection arrives, the algorithm tries to allocate slots from the previously allocated slots list using FF. If not enough previously used slots are available, it allocates slots that have never been assigned, also using FF. This strategy is employed in [37].

(9) Best-fit (BF): This method is a variation of EF. It checks a candidate route between a source and a destination node to find the sets of available FSs and sorts them according to their size, instead of in increasing index order like EF. The algorithm examines each set and allocates the one that exactly fits the demanded traffic, like EF. However, if no exact match is found, it allocates the set with the smallest size that satisfies that demand [20], [21]. Although BF was designed with the characteristics of the RSA problem in mind (i.e., it is not a straightforward adaptation of an RWA technique), the results in both [20] and [21] show that it achieves similar performance to FF when combined with single-path routing. However, in this paper we will demonstrate that its performance improves significantly when combined with a multi-path strategy (which we will discuss later), resulting in the proposed MP-BF algorithm.

(10) Multiple of n (Multi-n): Used in [40], the algorithm selects the required n FS so that the selected lowest-indexed FS is a multiple of n and the following n-1 FS are available.

All the techniques reviewed above to solve the RSA/RMSA problem in dynamic EONs are summarized in Table 3.

TABLE 3. Proposals to solve the dynamic RSA/RMSA problems.

Authors	Solving Strategy	Technique
Wan *et al.* [9]	Joint RMSA	Fixed or adaptive modulation selection + decision tree selection/modified Dijkstra's Shortest Path
Salani *et al.* [31]	Joint RSA and RMSA	ILP + Machine Learning techniques
Leiva *et al.* [32]	Joint RSA	Dynamic Graph Coloring
Velinska *et al.* [33]	Joint RMSA	Genetic Algorithm
Alyatama [35]	Joint RSA	Cost minimization heuristic
Agrawal *et al.* [36]	RM + SA	Routing: FR and FAR + modulation format Spectrum Assignment: FF
Jinno *et al.* [18]	RM +SA	Routing: FAR + modulation format Spectrum Assignment: FF
Calderón *et al.* [38]	RM + SA	Routing: FAR Spectrum Assignment: FF
Alyatama *et al.* [39]	R + SA	Routing: AR Spectrum Assignment: FF
Mukherjee *et al.* [2]	R	Routing: LCR
Sambo *et al.* [40]	RM + SA	Routing: LCR + modulation format Spectrum Assignment: FF, Multi-n
Yuan *et al.* [41]	RM + SA	Routing: FAR + modulation format Spectrum Assignment: FSs that minimize the available spectrum resource reduction
Takagi *et al.* [42]	RM + SA	Routing: FAR + modulation format Spectrum Assignment: FF
Ruiz *et al.* [19]	RM + SA	Routing: FAR + modulation format Spectrum Assignment: FF
Rosa *et al.* [43]	SA	Routing: - Spectrum Assignment: FF, RF, EF
Wang and Mukherjee [44]	RM +SA	Routing: FAR + modulation format Spectrum Assignment: FF, FLF, use of partitions
Christodoulopoulos *et al.* [4]	RM + SA	Routing: FAR + modulation format Spectrum Assignment: LLS
Fadini *et al.* [45]	R + SA	Routing: FR Spectrum Assignment: FLF
Li *et al.* [46]	R + SA	Routing: FAR Spectrum Assignment: FLF + fragmentation minimization
Chaterjee *et al.* [47]	R + SA	Routing: FAR Spectrum Assignment: FLEF
Ahumada *et al.* [20]	R + SA	Routing: FR Spectrum Assignment: BF
Abkenar *et al.* [21]	R + SA	Routing: FAR Spectrum Assignment: BF

C. TRAFFIC GROOMING, FRAGMENTATION AND SPLIT SPECTRUM TECHNIQUES

There are issues related to EONs as traffic grooming, fragmentation and split spectrum techniques that have an impact on the performance of RSA and RMSA algorithms. We will briefly introduce these aspects and describe their effects on the performance of RSA and RMSA algorithms.

1) TRAFFIC GROOMING

This operation aggregates low-speed connection requests into a higher capacity traffic flow to improve spectrum utilization. Traditionally employed in WRONs, it was introduced in EONs for two reasons: (i) it makes a better use of transponder capacity, given the limitations in slicing of early bandwidth-variable transponders (BVT) [7], and (ii) it improves the use of the spectrum since establishing less connections implies the use of less guard-bands between channels [7].

Traffic grooming can be performed electrically through the use of electrical subcarrier multiplexing and switching [48], [49]. However, this approach requires additional optical-electrical-optical (O/E/O) conversions and switching requirements at the intermediate nodes, increasing energy consumption [49], [50], [51]. Moreover, researchers developed the sliceable BVT (S-BVT), a device that overcomes the limitations of BVTs by supporting different modulation schemes, bit rate, transmission distances and sliceability [7], [49], [52]. These devices allow to partially perform traffic grooming at the optical layer, aggregating different low-capacity connections into one BVT and switching them as an optical tunnel or group of optical paths. Again, in order to separate different optical connections inside a network, a guard-band should be added [49], [50], [53].

Finally, traffic grooming can also be performed at the optical layer. Zhang *et al.* [50] presented an ILP formulation and a heuristic to plan the optical grooming minimizing either the consumed spectrum or the employed transponders in static and dynamic scenarios. Khodashenas *et al.* [54] proposed a heuristic to solve the RSA problem with traffic grooming that minimizes the used transmitters in the network. Zhu *et al.* [55] proposed a grooming algorithm based on deep reinforcement learning that extracts the state of the network and takes actions to decide where to groom a given IoT service with the goal of optimizing energy consumption. Hosseini *et al.* [56] proposed a heuristic to groom incoming traffic requests to existing lightpaths with remaining holding times close to the holding time required by the request, or establish a new lightpath aiming at efficiently using the spectrum and BVT resources. The proposals are summarized in Table 4.

TABLE 4. **Proposals on traffic grooming in EONs.**

Authors	Solving Strategy	Technique
Zhang *et al.* [50]	RSA+Traffic Grooming	ILP and heuristics to minimize either the consumed spectrum or the utilized transmitters
Khodashenas *et al.* [54]	RSA+Traffic Grooming	Heuristic to minimize the utilized transmitters
Zhu *et al.* [55]	Traffic Grooming	Deep reinforcement learning based algorithm to optimize the energy consumption
Hosseini *et al.* [56]	Traffic Grooming	Heuristic to optimize the use of spectrum and BVT.

2) FRAGMENTATION

The fulfillment of the continuity and contiguity constraints, together with the allocation and deallocation of FSs to connection requests, may cause fragmentation [57], i.e., the appearance of isolated idle FSs, almost unusable for the establishment of new connections, thereby increasing blocking events.

Fragmentation can be addressed through an operation called defragmentation. This approach periodically reconfigures the existing connections and allocated spectrum. In consequence, the misuse of spectrum resources and bandwidth blocking are reduced [5], [7], [57]. There are different defragmentation techniques like the hop-tuning, the make-before-brake and the push-and-pull approaches [5], [7]. The hop-tuning strategy [58] moves the assigned slots to a connection to other available slots, while keeping the route. The push-and-pull technique [59] changes the allocated slots by increasing the assigned resources, pushing the central frequency as close as possible to the side of the adjacent connection and reducing the allocated resources to the original number of assigned FSs. Finally, the make-before-break approach [60] provisions a new connection between the source and destination nodes of the lightpath to be defragmented. The traffic then shifts from the old to the new connection and the original one is torn down.

Furthermore, fragmentation can be managed through the RSA algorithms. Dávalos *et al.* [61] proposed an algorithm based on ant colony optimization and a genetic algorithm to solve the RSA problem. The algorithms decide the best set of lightpaths to be proactively rerouted, with the objective of reducing the request blockage. Moura *et al.* [62] proposed a heuristic to solve the RSA problem using a multigraph, i.e., a graph where vertices can have multiple edges. In this case, the vertices are the optical cross connects (OXC) of the network and there are as many edges connecting the OXCs as FSs in the spectrum of each link. Authors, then, calculate the number of FSs required to satisfy the connection request and propose a heuristic that uses the graph to select the single path and portion of spectrum to be allocated that minimizes the overall power consumption and bandwidth blocking. Waldman *et al.* [63] proposed a deadlock-avoidance technique that reduces fragmentation by assigning network resources only if the allocated link is fully utilized after reserving resources, or if the remaining resources can accommodate another connection. Qiu *et al.* [64] presented a spectrum consumption model that takes into consideration the occupied spectrum, the fragmented spectrum, and their holding times. They proposed an ILP formulation that minimizes the spectrum consumption obtained with this model, with the objective of minimizing the bandwidth blocking. They also devised a heuristic to solve the RSA problem in dynamic scenarios adapting the model to the characteristics of dynamic traffic. This heuristic calculates the k-shortest paths and, for each candidate path, finds the set of available FSs, calculates the spectrum consumption including the fragmented FSs, and allocates the path and portion of spectrum that minimizes this consumption. Yuan *et al.* [65] proposed an RSA to minimize the blocking ratio by modeling the fragmentation through the concept of contiguity reduction, which measures the reduction in the adjacency degree of available frequency slots, when a new connection is established. The algorithm computes the shortest path between the source and destination nodes, checks the blocks of available FSs in increasing size order, computes the path and link contiguity reduction and selects the available FSs that minimize the fragmentation in terms of path contiguity reduction and using the lowest link fragmentation in case of tie. Adhikari *et al.* [66] addressed the spectral and the spatial fragmentation problem using an spectrum allocation algorithm. They proposed an RSA algorithm that computes the k-shortest paths between source and destination nodes, and then selects those that meet a certain BER threshold. Once the candidate path set is built, the algorithm checks, for each route, each set of available FSs and selects the route and the FSs that minimize the spectral fragmentation. If two candidates present the same minimum value of spectral fragmentation, the algorithm selects the one with the lowest spatial fragmentation. Liu *et al.* [67] also addressed the time and spectrum fragmentation problem by proposing an RMSA algorithm for advance reservation requests. The algorithm relies on pre-computed k-shortest hop paths and k-shortest distance paths between each source-destination pair of nodes. When a request arrives at the network, it dynamically calculates the routing weight of those paths as the occupied spectrum resources, and then selects candidate paths according to their increasing order of routing weight. Next, for each candidate path, the algorithm computes the available spectrum resources and selects the route that minimizes the spectrum fragmentation, measured as the fragmentation in the selected route and in those routes with shared links. These algorithms are summarized in Table 5.

TABLE 5. Proposals to address the fragmentation problem using routing and spectrum allocation algorithms.

Authors	Solving Strategy	Technique
Dávalos *et al.* [61]	RSA	Ant colony optimization and genetic algorithm
Moura *et al.* [62]	RSA	Multigraph + heuristic
Waldman *et al.* [63]	SA	Deadlock-avoidance allocates only if full link utilization is produced of the remaining resources can accommodate future requests
Qiu *et al.* [64]	RSA	ILP and heuristic. k-shortest paths + spectrum assignment that minimizes spectrum consumption, including fragmented spectrum and holding times
Yuan *et al.* [65]	RSA	Shortest path + spectrum assignment that minimizes the path contiguity reduction
Adhikari *et al.* [66]	RSA	k-shortest paths + spectrum allocation that minimizes the spectral fragmentation or the spatial fragmentation in case of ties
Liu *et al.* [67]	RMSA	k-shortest paths + spectrum allocation that minimizes time and spectrum fragmentation in the selected path and routes with shared links

3) SPLIT SPECTRUM TECHNIQUES

The elastic features of EONs allow providing the total requested capacity through multiple connections of smaller capacity (sub-lightpaths) that can be routed through the same or different paths. If the same path is used for all sub-lightpaths, it is known as single-path routing, while if different paths can be used for each sub-lightpath, the term multi-path routing is employed.

Zhu *et al.* [68] proposed two heuristics to solve the RMSA problem, which combine multi-path routing together with the FF spectrum assignment technique. One of the algorithms calculates the k-shortest paths at the connection arrival time, taking into account current network status, and then checks each path in ascending weighted length order and allocates the first available FSs. The other algorithm pre-calculates a set of fixed candidate paths using k-shortest paths. Then, when a connection request arrives, the algorithm updates the available resources, sorts the pre-calculated set of paths according to different strategies and checks each path to find available resources, allocating the FSs using the first-fit algorithm. Authors in [69] presented a heuristic to solve the RMSA problem considering a bi-dimensional resource model that contains the spectrum availability in the time domain. The algorithm initially tries to allocate each request in a single connection using FF as the spectrum assignment technique. If there are blocked connections, the algorithm tries to allocate them by splitting the traffic of each demand into three sub-lightpaths routed through the same path. Finally, if there are requests that could not be allocated, the algorithm tries to route them through different paths. When the connections are provisioned using the multi-path technique, the heuristic selects the paths and FSs that minimize the fragmentation, calculated as the difference between the time and spectrum fragmentation before and after the resource reservation.

Yousefi *et al.* [70] proposed different heuristics to solve the RMSA problem applying the multi-path approach. If the request cannot be provisioned in a single connection solved using the k-shortest paths and first-fit, the algorithm splits the request into two different sub-lightpaths independently provisioned. The set of candidate paths are calculated using the k-shortest paths and checked according to some criteria like the external fragmentation or fragmentation measure metric proposed by the authors, while the algorithm assigns the first set of available FSs that satisfy the traffic demand. In our work in [19], the classic RWA methods k-shortest paths and first-fit were adapted to be solve the RSA problem considering either flexgrid or gridless spectrum and single-path and multi-path routing. Our study shows that traditional RWA techniques are not able to fully exploit the flexibility of EONs. Pagès *et al.* [15] proposed a heuristic to solve the RSA problem combining a single-path approach and a flexible spectrum allocation strategy. The algorithm computes the k-shortest paths between the source and destination node, sorts the sets of available FSs in decreasing size order and, for each feasible path, starts allocating the sets of FSs in order until all the traffic is served. A guard-band is added after each sub-lightpath to avoid interference between adjacent connections. Therefore, a request is blocked if no candidate path can satisfy the demanded traffic plus the required guard-bands or if the traffic is split in more sub-lightpaths than the allowed. The same authors presented in [71] a heuristic to solve the RMSA problem. The technique employs a greedy approach to build the set of candidate paths to serve the request and sorts it according to a quality criterion that includes the number of allowed modulation formats in the path and the number of FSs required to serve the request utilizing each of the feasible modulation formats. Once the candidate path set is built, the algorithm checks each one and the availability of spectral gaps in decreasing size order to favor the allocation of a demand in fewer parts (i.e., reducing the number of required sub-lightpaths). If the algorithm cannot serve the traffic demand or if the connection needs to be split into more parts than those allowed, the request is blocked.

One disadvantage of multi-path routing techniques is that the different sub-lightpaths experience different end-to-end delays. Some works have addressed this drawback by setting constraints on the maximum differential delay between paths [72], [73], and have analyzed the impact on buffering costs required to solve that problem [74].

All these proposals, which implement split spectrum techniques are summarized in Table 6.

TABLE 6. Proposals using split spectrum techniques.

Authors	Problem Solved	Technique
Zhu *et al.* [68]	RMSA	On-line *k*-shortest paths+ FF Pre-calculated *k*-shortest paths, on-line sorting + FF
Zhu *et al.* [69]	RMSA	*k*-shortest paths, fragmentation in the same or in different paths and spectrum allocation that minimizes spectrum and time fragmentation
Yousefi *et al.* [70]	RMSA	*k*-shortest paths sorted according to different criteria + FF
Ruiz *et al.* [19]	RSA	Combination of multi-path, first-fit and flexgrid and gridless spectrum
Pagès *et al.* [15]	RSA	*k*-shortest paths, selection of candidate paths with enough FSs to satisfy the demand, "biggest first" spectrum allocation
Pagès *et al.* [71]	RMSA	Greedy algorithm to build the candidate path set, "biggest first" spectrum allocation
Lu *et al.* [72]	RSA	Multi-path routing + FF, including a constraint on the maximum differential delay between paths.
Chen *et al.* [73]	RSA	Heuristic, including constraints on maximum differential delay.
Zhang *et al.* [74]	RSA	Heuristic, including a constraint on maximum differential delay. Buffering costs are studied.

In this paper, we propose a RMSA algorithm for dynamic EONs called multi-path best-fit (MP-BF). Our proposal uses the k-shortest paths technique and allows to use the multi-path routing strategy to solve the routing problem and the best-fit technique (BF) for the spectrum assignment, and we demonstrate that it outperforms other RMSA methods.

III. NOVEL RMSA ALGORITHM: MULTI-PATH BEST-FIT (MP-BF)

A. ALGORITHM DESCRIPTION

The dynamic RMSA problem is solved in a dynamic EON when a user connection request arrives at the network. In that moment, the network must determine the modulation format, the route, i.e., the sequence of fibers from the source to the destination node, and a portion of spectrum to satisfy the requested bandwidth. If the network is not equipped with waveband/wavelength converters, the reserved portion of spectrum along the fibers of the route must be the same. This restriction is known as the spectrum continuity constraint. When there are not enough idle resources to satisfy the request, the demand is rejected. Otherwise, the connection is established [11]. The goodness of the RMSA methods is usually measured in terms of different indicators: blocking ratio (i.e., the ratio of rejected user demands), the carried traffic, the consumed energy or the computing time required to find a solution.

The RMSA method proposed in this paper is called multi-path best-fit (MP-BF), and it combines the multi-path routing technique, using FAR, with the best-fit algorithm [20], [21]. In contrast to the algorithms in [20], [21], where only single-path is allowed, MP-BF improves the network performance by allowing the split of the required capacity into multiple sub-lightpaths if a single route with enough idle spectrum is not available. The different sub-lightpaths can be routed through the same path or through a different route, but the sum of their capacity must satisfy the one requested by the user. Moreover, [20], [21] are RSA methods but MP-BF solves the RMSA problem and thus, it also selects the modulation format. In particular, MP-BF uses the most efficient modulation format that ensures the fulfillment of QoT requirements. Note that each sub-lightpath can use different modulation formats and, consequently, can have different spectral efficiencies. That feature is also considered by MF-BF. Similarly to other studies on this topic [71], the issue of the differential delay among parts is left out of the scope of this study. The use of multi-path routing implies that the wasted spectrum in guard-bands increases with the number of sub-lightpaths created for each connection, given that each sub-lightpath requires the addition of a guard-band. Despite that, the flexibility given by the multi-path routing when combined with the BF technique takes MP-BF to beat the performance of those methods as it will be demonstrated later.

The pseudocode of MP-BF is shown in Algorithm 1. Initially, a set of candidate routes for each pair of nodes using the k-shortest paths (in terms of hops) is pre-computed. Then, when a new lightpath establishment request between the source node s and the destination node d arrives, MP-BF sets the value of the pending capacity to be assigned to the requested capacity (line 2) and retrieves the set of k-shortest paths for that s-d pair, sorted in increasing length order (line 4). Next, MP-BF searches in each path portions of idle spectrum to establish the request (lines 5-25). Note that the MP-BF stops as soon as it finds a solution (either using a single lightpath or several sub-lightpaths) that provides the requested capacity.

MP-BF uses the most efficient modulation format for each path taking into account its physical length (in kilometers), as done in [4], [18], [71] (line 6). When checking the available spectrum in a candidate route, MP-BF obtains the set of contiguous idle FSs in all the fibers of the path to ensure the spectrum continuity constraint (line 7). We assume that the guard-band is included in the last slot of the assigned set of contiguous FSs. Therefore, we can obtain the capacity of the

Algorithm 1 : MP-BF

```
1:  procedure MP-BF(source, destination,
      requestedCapacity)
2:    pendingCapacity ← requestedCapacity
3:    selectedSetsOfFS ← ∅
4:    paths ← retrieveKShortestPaths(source,
      destination)
5:    for path in paths do
6:      modulation ← selectBestModulation(path)
7:      # Groups of contiguous idle FSs in the path
        setList ← getSetsOfContiguousFS(path)
8:      for set in setList do
9:        set.capacity ← computeCapacity(set,
          modulation)
10:     end for
11:     setList ← sort(setList, by =capacity,
                        order=increasing)
12:     while setList ≠ ∅ do
13:       for set in setList do
14:         if set.capacity ≥ pendingCapacity then
15:           # Use only the required spectrum (slots)
              of that set
              set ← reduceSize(set, pendingCapacity)
16:           selectedSetsOfFS ← selectedSetsOfFS
              ∪ set
17:           establishSubLightpaths(selectedSetsOfFS)
18:           go to end procedure
19:         end if
20:       end for
21:       # Extract the last set of FSs of the list
          highestCapacitySet ← pop(setList)
22:       selectedSetsOfFS ← selectedSetsOfFS ∪
                              highestCapacitySet
23:       pendingCapacity ← pendingCapacity -
                          highestCapacitySet.capacity
24:     end while
25:   end for
26:   blockConnection()
27: end procedure
```

set, i.e., the rate at which the traffic can be transported over this group of available FSs, by subtracting the guard-band bandwidth from the sum of the bandwidth of all the consecutive available slots in this set and multiplying the resulting value by the spectral efficiency of the selected modulation format for that path (lines 8-10). The channels are then sorted in increasing capacity order (line 11).

Here, an iterative process with the available set of contiguous FSs in the path begins, and it continues until the demand is served or until all the sets in the path are checked (lines 12-24). If no set of contiguous available FSs in the path has enough capacity to satisfy the pending one, the use of several sets of contiguous FSs (and thus sub-lightpaths) will be required, hence splitting the demand. We will later describe that procedure. In contrast, if there are several sets that provide equal or more capacity than the pending one, MP-BF selects the one that has the closest capacity to the pending capacity (lines 14-16). This is because the sets of contiguous FSs were sorted in increasing order of capacity. In case of tie, MP-BF uses LF with the tied sets of contiguous FSs. It is worth noting that the size of the selected set is reduced to only use the required number of FSs to provide the pending capacity (line 15). That number is computed in a similar way as described before (i.e., taking into account the guard-band bandwidth, the bandwidth of the slots and the spectral efficiency). Then, MP-BF uses the sets that have been selected along the iterative procedure to establish optical connections (one sub-lightpath per selected set) and the process finishes (lines 17-18).

If all the sets of contiguous FSs in the path have less capacity than the pending one (line 14 is not fulfilled), the demand cannot be served with a single set of FSs; thus, MP-BF splits the demand. First, it selects the set with the highest capacity to be later used to establish a sub-lightpath and deletes it from the list of (available) sets (lines 21-22). Since part of the pending capacity will be provided by that sub-lightpath, the pending capacity is updated by subtracting the capacity of that set of FSs (line 23). The process continues with a new iteration of the 'while' loop (line 12), looking for a set of contiguous FSs in the path that best fits the pending traffic, or splitting again the demand until the requested capacity is served, or all sets of contiguous FSs in the path are checked and assigned.

If all the sets of contiguous, available FSs of the candidate path have been checked and assigned, and there is still pending capacity to be satisfied, MP-BF continues with the next path following the same procedure as described above. If MP-BF tries all the pre-computed paths but there still is pending capacity to accommodate, the request is blocked (line 26). Note that a connection is only established if the network can fully satisfy the requested bandwidth (line 17). The algorithm does not impose any limitation in the number of splits, neither in the same route nor in different routes.

Fig. 1 illustrates how MP-BF works in a sample scenario. Let us assume a connection request from A to C arrives at the control plane of the 6-node network shown in the figure. The shortest path between those nodes goes through A→B and B→C links. The current spectrum utilization of those links and of the path (the combination of both link spectrum utilizations) is also shown in Fig. 1. Let us assume that the size of guard-bands in this scenario is one slot.

In the first example, the A to C connection request demands a capacity equal to one slot. Therefore, two consecutive empty spectral slots are required (one to provide the requested capacity, which will be represented in red in Fig. 1, and one for the guard-band, represented in green). MP-BF assigns the portion of spectrum that best fits the demand (as shown in Fig. 1, E.g. 1). In contrast, if MP-FF had been used, the first

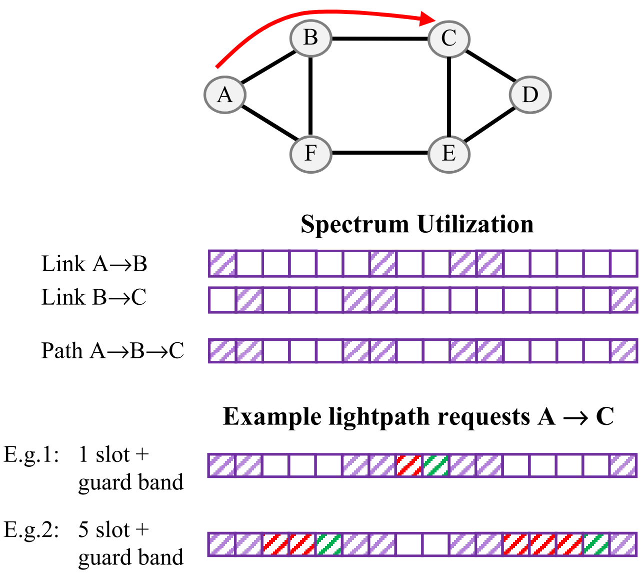

FIGURE 1. Spectrum allocation when using MP-BF when 1 FS is requested (E.g. 1) and 5 FSs are requested (E.g. 2).

two empty slots would have been assigned, thus leaving one idle (and unusable) slot in the spectrum.

In the second example, the request demands a capacity equal to five slots. In this case, single path techniques cannot provide the required spectrum through the A→B→C path. Therefore, the lightpath should be either established in a longer route with enough consecutive FSs or rejected. In contrast, MP-BF uses a multi-path technique. Thus, it will split the request into two sub-lightpaths (including the required guard-bands) and establish the request as shown in Fig. 1 (E.g. 2). If MP-FF had been used instead of MP-BF, three sub-lightpaths (with three guard-bands) would have been established to satisfy the request and, thus, it would have used more spectrum than MP-BF.

B. COMPLEXITY ANALYSIS

The complexity analysis of MP-BF is derived from Algorithm 1. Let K be the number of candidate paths, S the total number of FS in a link and L the number of links. Since the candidate paths are pre-computed (as well as their best modulation format depending on their physical distance in km), its complexity is not considered. There is a "for" loop (lines 5-25) which repeats K times. That loop internally contains different operations. First, the precalculated best modulation format of the precalculated path is retrieved ($O(1)$), and the sets of contiguous FS in that path are searched (line 7), which has a complexity $O(LS)$. Then, the capacity of those sets is computed in lines 8-9, which has complexity $O(S)$, and they are sorted in line 11, which has complexity $O(S \cdot log(S))$. Next, the "while" loop (lines 12-24) assigns the spectrum using the BF policy. Since the "while" loop contains a "for" loop (lines 13-20) that checks all the channels in the channel list and is completed in S steps in the worst case, the complexity of the while loop is $O\left(S^2\right)$, which dominates over the $O(1)$, $O(S)$ and $O(S \cdot log(S))$ complexities previously mentioned. Therefore, the total computational complexity of MP-BF is $O\left(K\left(S^2 + LS\right)\right)$.

IV. PERFORMANCE EVALUATION OF MP-BF

A. SIMULATION SETTINGS

The performance of MP-BF has been compared with other proposals from the literature by means of a simulation study. For that aim, an EON simulator was implemented using OMNeT++ [75]. The physical topology of the network used in the simulation is the 14-node NSFNet [76], where each link is composed of two unidirectional optical fibers, one for each direction. All channels belong to the C-band and, therefore, the available bandwidth of each fiber is 4 THz. As in most studies, flexgrid technology is considered using FSs of 12.5 GHz, and assuming 10 GHz of guard-band between contiguous lightpaths or sub-lightpaths. Nodes are assumed to be equipped with transceivers able to use four modulation schemes: BPSK, QPSK, 8-QAM and 16-QAM. The bits per symbol, spectral efficiency, transmission rate per full slot, and optical reach of each modulation format are shown in Table 7 [4], [77]. Like in most studies in the area, we have assumed that blocking is only due to lack of spectrum and not to lack of transponders, unless otherwise stated.

TABLE 7. Transmission rates and optical reach of the different modulation schemes.

Modulation Scheme	Bits per symbol	Spectral efficiency	Transmission rate per full slot [74]	Optical Reach [4]
BPSK	1	1 b/s/Hz	12.5 Gb/s	3000 km
QPSK	2	2 b/s/Hz	25 Gb/s	1500 km
8-QAM	3	3 b/s/Hz	37.5 Gb/s	750 km
16-QAM	4	4 b/s/Hz	50 Gb/s	375 km

We also assume that connection requests arrive at the network following a Poisson process with arrival rate, λ. The source and destination nodes for each request are randomly selected using a uniform distribution. Each connection demands a capacity randomly generated using a uniform distribution between $C_{min} = 1$ Gbps and $C_{max} = 300$ Gbps, therefore with average $C_{avg} = (C_{max} - C_{min})/2$. Finally, the holding time for each connection is generated by means of an exponential distribution with mean equal to $T = 60$ s. Since different connections demand different capacities, rather than using the classical traffic load in erlangs, computed as λT, we use a normalized version of it. It is given by equation (1), which takes into account the average and maximum capacity of the connections, as well as the number of nodes in the network, N.

$$load = \frac{\lambda T}{N(N-1)} \cdot \frac{C_{avg}}{C_{max}} \tag{1}$$

B. COMPARISON ALGORITHMS

Our proposal, MP-BF, has been compared with five other algorithms, previously presented in Section 2, which have proven their efficiency to solve the RMSA problems: multi path-first fit (MP-FF) [68], [70], multi path-exact fit (MP-EF), single path-first fit (SP-FF) [18], single path-exact fit (SP-EF) [43] and single path-best fit (SP-BF) [20], [21].

MP-FF uses precalculated multi-path, k-shortest paths for routing and FF for spectrum allocation. MP-EF also precalculates k-shortest paths but uses EF to assign the spectrum. The SP-FF method works like MP-EF but using single path routing. Note that single path routing means that a connection request cannot be split in different sub-lightpaths, in contrast to the MP methods. However, precalculated k-shortest paths are also used for route selection in SP-FF. SP-EF [43] works like SP-FF, but using EF as the spectrum assignment technique. Finally, SP-BF [20], [21] uses single path routing with precalculated k-shortest paths, but using the BF technique for spectrum allocation instead of FF. In all cases, the most efficient modulation format that ensures the fulfillment of QoT requirements has been considered for each path.

Unless otherwise stated, the six algorithms calculate 5 routes to determine the k-shortest paths ($k = 5$). Simulations with other values of this parameter ($k = 1, 3, 7$) were also analyzed leading to the same conclusions as the ones that will be presented in the next subsections.

C. RESULTS

The six methods have been compared in terms of different parameters: blocking ratio, energy consumption, and computation time. First of all, Fig. 2 shows the request blocking ratio obtained when using the different methods. This parameter is especially important for improving the perception of the final users and it clearly affects the quality of experience (QoE) and the operator reliability. For all the methods, the request blocking ratio increases when the network load grows. As in [20], [21], SP-BF obtains a similar request blocking ratio to that achieved by SP-FF and SP-EF, in the same order of magnitude for all network loads. However, when comparing the six methods, MP-BF clearly outperforms the other proposals. For instance, for traffic loads around 0.4 the blocking ratio for MP-BF is more than one order of magnitude lower than SP-based methods and more than three orders of magnitude lower than MP-FF and MP-EF. This means that, if we set the maximum admissible request blocking ratio to 10^{-3} and compare the performance of MP-BF with the SP methods (which are the next best performing methods), when using MP-BF, the network can support network loads of up to 0.5, while it supports around 0.4 for SP methods (i.e., around 25% more traffic with MP-BF).

The use of multi-path routing has potential for establishing connections that otherwise would be blocked, by splitting the demand in several sub-lightpaths, but this may lead to higher spectrum fragmentation, and it also implies that the wasted spectrum in guard-bands increases (given that each sub-lightpath requires the addition of a guard-band). Therefore, these connections occupy more spectral resources, which in turn negatively affect to future requests. Hence, there is a trade-off between these factors, and in some cases, like when FF or EF spectrum assignment techniques are used, the advantages of multi-path routing do not outweigh the disadvantages. In contrast, the BF technique is more efficient in this scenario (since it helps reducing the number of splits needed to serve the demands, as it will be later demonstrated), thereby reducing the blocking ratio as shown in Fig. 2. However, when the traffic load is high, the multi-path approach does not compensate for the wasted bandwidth due to additional guard-bands, even when using BF. Nevertheless, the blocking ratios for these high traffic loads are around 0.1, and no network operator would be interested in operating the network with such poor performance. Therefore, if we focus on pragmatic scenarios, with a low blocking ratio (which corresponds to low to medium traffic loads), the combination of multipath routing with BF makes better use of the available spectrum to reduce the blocking ratio by more than one order of magnitude, resulting in approximately 25% more supported traffic compared to SP methods.

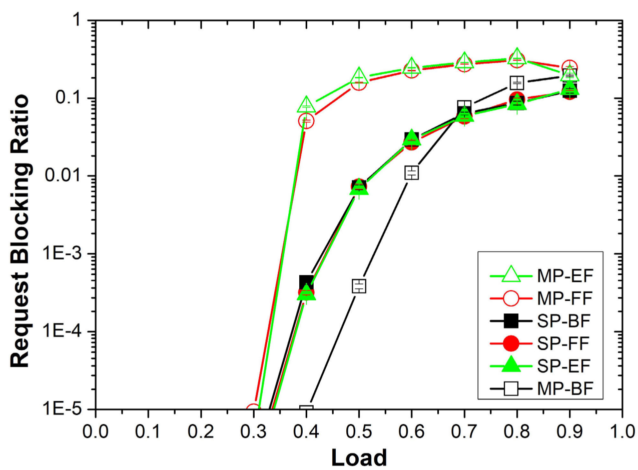

FIGURE 2. Request blocking ratio obtained by MP-BF, MP-EF, MP-FF [68], [70], SP-BF [20], [21], SP-EF [43] and SP–FF [18] considering *k* = 5 shortest paths.

Next, Fig. 3 shows the request blocking ratio obtained with SP-FF and MP-BF (the best methods from the previous figure) for different values of k (1, 3 and 5). The figure shows that increasing the number of candidate paths reduces the request blocking ratio of both algorithms. However, the reduction decreases as k increases. Comparing the performance of the two algorithms, the blocking ratio using MP-BF is lower for all values of k.

In order to check whether the improvement in performance of MP-BF comes at a cost, we have evaluated three different issues: the network energy consumption, the required number of transponders and the computing time required by the different algorithms.

Thus, we have first analyzed whether the increment in the supported traffic translates into more energy consumption in the network or not. As the dynamic EON in the study carries the traffic from the source to the destination node using direct lightpaths (i.e., without Layer 2 and/or Layer 3 routing

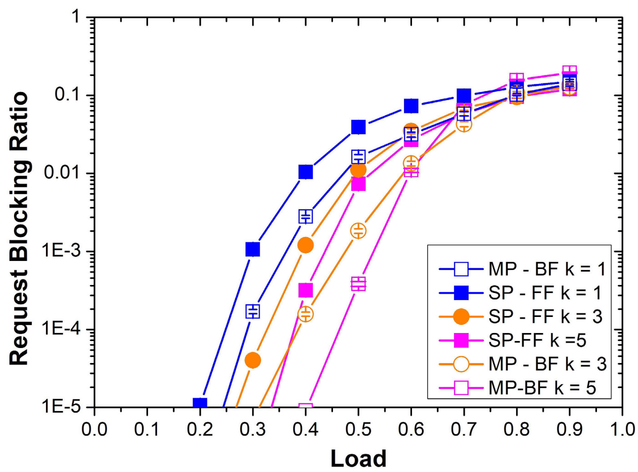

FIGURE 3. Request blocking ratio obtained by of MP-BF and SP–FF [18] for increasing values of k.

at intermediate nodes), only the energy consumption of the optical layer has been considered. For that aim, the EON energy model proposed by Lopez *et al.* [77] was implemented in the EON simulator. It provides power consumption models for transponders, optical cross connects (OXCs) and optical amplifiers (in particular, erbium doped fiber amplifiers, EDFAs), taking into account issues like modulation formats, transmission rates, and the number of ports of the OXCs. Using those models, the energy consumption per bit when employing the six RMSA algorithms was computed. Thus, Fig. 4 shows the energy efficiency in watt-hour per bit (W·h/b) for different traffic loads and using the different methods.

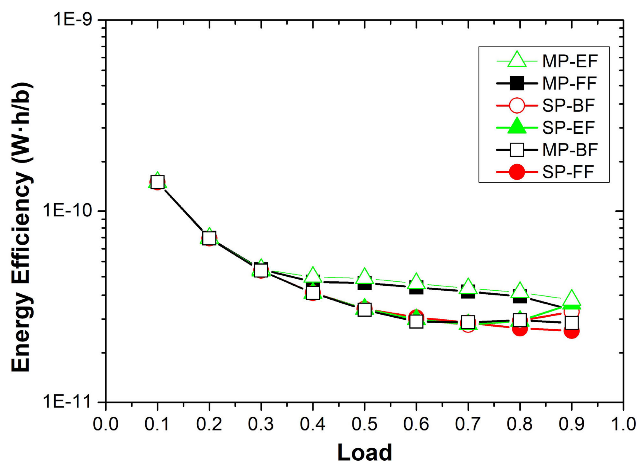

FIGURE 4. Energy efficiency of MP-BF, MP-EF, MP-FF [68], [70], SP-BF [20], [21], SP-EF [43] and SP–FF [18] considering $k = 5$ shortest paths.

As it can be seen in Fig. 4, the use of MP-BF, which is the most efficient method in terms of supported traffic (Fig. 2), does not translate in higher energy consumption in the network. The energy efficiency obtained using this method is roughly equal to that of the SP methods for all loads except for traffic loads higher than 0.8 but, as we have previously discussed, that is not a pragmatic scenario as the blocking ratio is too high. Moreover, MP-BF outperforms MP-FF and MP-EF achieving an energy consumption up to 36% lower than MP-EF and up to 33% lower than MP-FF. Therefore, Fig. 2 and Fig. 4 show that the combination of multi-path routing with the BF approach for spectrum allocation significantly outperforms the combination with FF.

Nevertheless, splitting the demanded traffic into several sub-lightpaths, either routed over the same route or traveling over different paths may lead to an increase of the complexity of the network, since it may induce the utilization of more transponders, as well as additional spectrum waste due to having more guard-bands (one per sub-lightpath), as previously mentioned. In order to explore these issues in more detail, we have first analyzed the average number of sub-lightpaths required to serve the demand when using the multi-path approaches.

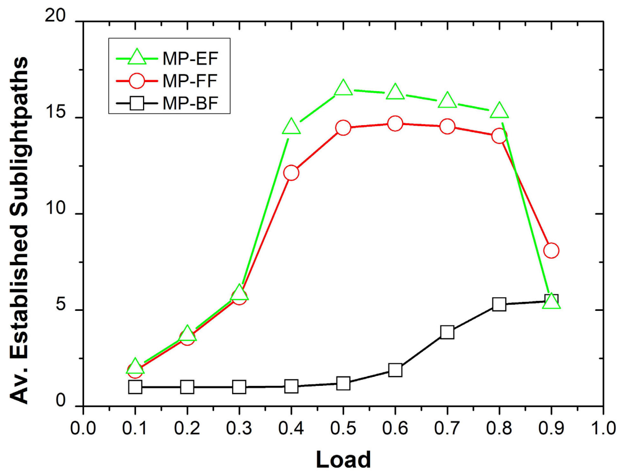

FIGURE 5. Average number of sub-connections required by MP-BF, MP-EF and MP-FF [68], [70], considering $k = 5$ shortest paths.

As shown in Fig. 5, MP-FF and MP-EF split the traffic demands into up to about 15 sub-connections for medium traffic loads. In contrast, MP-BF uses fewer sub-connections per request, splitting an average of up to 1.2 sub-lightpaths for medium traffic loads. This behavior is due to the fact that FF and EF assign the first available set of FSs (unless there is a set of FSs that exactly matches the pending traffic, if EF is used), hence leading to more splits compared to MP-BF and, consequently, increasing the required guard-bands between connections. Contrarily, BF assigns either the smallest set of available and contiguous FSs where the demand fits, or if it does not fit in any set, it uses the largest available set of FSs to partially serve the demand (line 21 in Algorithm 1), thus reducing the number of required splits and the associated number of guard-bands. In this manner, MP-BF makes a better use of the spectrum and results in the reduction of the request blocking ratio up to more than one order of magnitude compared to other techniques, as shown in Fig. 2, and in energy savings of up to 36% compared to other multi-path techniques, as shown in Fig. 4.

We now turn our attention to the impact on transponders. Split spectrum techniques involve generating multiple optical flows (sub-lightpaths) starting from a single node. From the transponder point of view, there are two main approaches to support this, either using a different bandwidth variable transponder (BVT) for each sub-lightpath to be established or equipping each node with a sliceable bandwidth variable transponder (S-BVT). In the latter case, a single transponder in each node is able to generate multiple sub-lightpaths, each using a different portion of the optical spectrum, and which may be routed through different paths through the EON [52]. In summary, the use of split spectrum techniques involves using either a higher number of transponders or a more complex architecture of the transponders.

In order to analyze the impact of transponders in performance, Fig. 6 shows the blocking ratio of MP-BF and SP-FF, as a function of the maximum number of sub-lightpaths that can start at a node. If the first approach is used (one BVT per sub-lightpath), that number represents the number of BVTs per node. If the second approach is used (a single S-BVT per node), that number represents the maximum number of sub-lightpaths that can be generated by the architecture of the S-BVTs employed in the network.

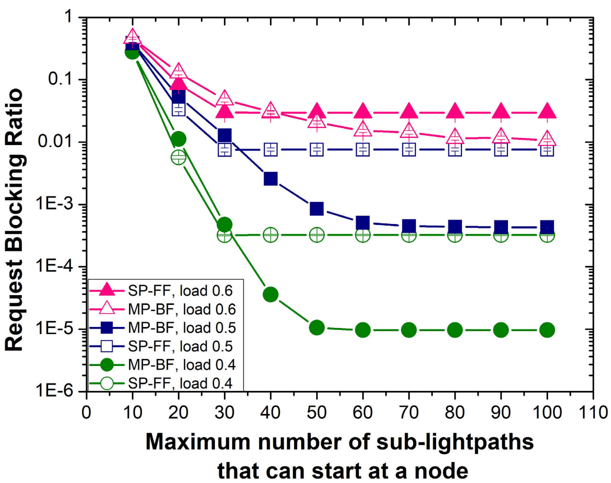

FIGURE 6. Request blocking ratio of MP-BF and SP-FF [18] as a function of the maximum number of sub-lightpaths that can start at a node, considering k = 5 shortest paths.

We have considered different traffic loads (from 0.4 to 0.6) and the use of 5 shortest paths. For that simulation setup, the multipath technique brings advantages in terms of request blocking ratio over the single path option when a node is able to be the source of around 30-40 sub-lightpaths. Therefore, if S-BVT are used, and have potential to generate more than those sub-lightpaths, improvements on blocking probability higher than one order of magnitude can be achieved. For instance, if the S-BVT can be the source of 70 sub-lightpaths, for SP-FF and a traffic load of 0.5, the request blocking ratio is slightly below 10^{-2} (around $8{\cdot}10^{-3}$), while for MP-BF the blocking ratio is well below 10^{-3} (around $4.5{\cdot}10^{-4}$). Let us now consider that BVTs are used. When a low number of BVTs per node are used, the results in blocking ratio are similar for MP-BF and SP-FF (very slightly better for SP-FF, as shown in Fig. 6). However, the use of MP-BF provides the operator with an additional option to upgrade the network to support traffic increases. For instance, let us assume that the aim is to operate the network so that the request blocking ratio is lower than 10^{-3}. As shown in Fig. 6, when using 30 transponders with SP-FF or with MP-BF the network can support a traffic load of around 0.4. If the traffic load increases to 0.5, the operator might opt for adding new transponders per node (reaching 50 per node) together with MP-BF to still have a blocking ratio below 10^{-3}. In contrast, if SP-FF were used, the blocking ratio would exceed that value (it would be around $8{\cdot}10^{-3}$), and adding transponders would not reduce the blocking ratio, so that the operator could only opt for adding spectral resources (even if that were less cost effective). Thus MP-BF provides more flexibility to the operator when trading off the costs required to upgrade the network (increasing transponders or spectral resources) to support higher future traffic loads.

The complexity analysis of MP-BF has been shown in Section III.B. The five baseline algorithms to which our proposal is compared have an analogous structure, i.e., a "for" loop that is completed in a maximum of K cycles, a "for" loop to compute the available channels that is completed in LS steps and a "while" loop with a "for" loop inside to assign the available spectrum having the same worst-case scenario. Therefore, the complexity of those algorithms is also $O\left(K\left(S^2+LS\right)\right)$. However, this is the worst-case scenario, and it could be reasonable to think that multi-path routing and the use of BF approach could involve higher computing time. For this reason, we have also analyzed the execution time of the algorithms. Fig. 7 shows the computational times of the studied algorithms for different network loads. MP-EF and MP-FF are the most computationally demanding methods, as they split the demand in many low-bandwidth sub-lightpaths. However, MP-BF presents the same computational time than SP-FF, SP-EF and SP-BF for low and medium loads, since it efficiently splits the demands, showing only up to 1.2 average splits per connection for medium loads. Only for loads higher that 0.6 the computation time for MP-BF significantly increases when compared with SP-based algorithms, being up to 2.5 times higher than SP-EF, SP-FF and SP-BF for a load of 0.9, since it checks more sets of available FSs in different candidate paths until satisfying the demanded traffic, if possible. Nevertheless, as previously discussed, the network would not operate at those loads since the blocking ratio would be too high. In any case, the times required by the studied methods are below 200 ms (and below 20 ms for loads lower than 0.5), which is much less than the time required to establish a lightpath.

Hence, MP-BF is the most efficient method. It achieves the lowest blocking ratio, thus supporting a higher traffic load in

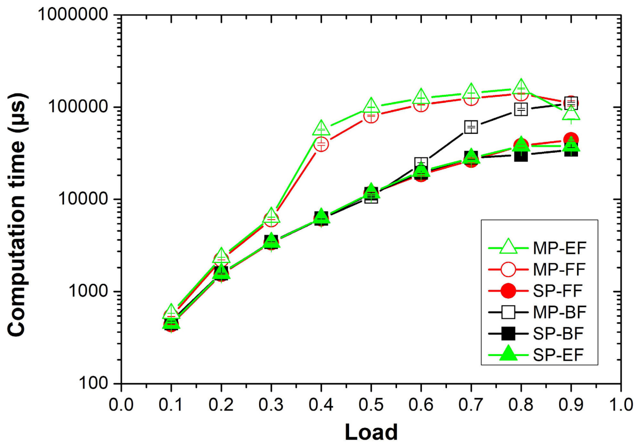

FIGURE 7. Computation times of MP-BF, MP-EF, MP-FF [68], [70], SP-BF [20], [21], SP-EF [43] and SP–FF [18] considering $k = 5$ shortest paths.

the network (Fig. 2). This improvement in performance does not imply paying a cost in terms of energy efficiency in the network (Fig. 4), nor in terms of computational time (Fig. 7). This is because multi-path routing and best-fit techniques complement each other really well, splitting the demand only when it really brings advantages (Fig. 5), resulting in excellent performance results.

V. CONCLUSION

In this paper, we have presented a comprehensive review of the main references in the area of RSA/RMSA problems, both in static and dynamic scenarios, for elastic optical networks. Then, we have proposed a new RMSA algorithm for dynamic scenarios called MP-BF. The novelty of the MP-BF algorithm relies on combining multi-path routing (which allows splitting the demand and serving it by means of multiple sub-lightpaths) with an efficient spectrum allocation technique, best-fit (which assigns the set of available FSs that best fits the traffic demand). Previous studies on the best-fit method had only analyzed its performance when combined with single-path routing, and we have demonstrated that best-fit unveils its potential when combined with a split spectrum approach.

The performance of MP-BF has been compared with that of five efficient RMSA algorithms proposed in the literature. The results of this comparison clearly show that the use of MP-BF in an EON allows to decrease the blocking ratio more than one order of magnitude without increasing the network energy consumption or the computation time. In particular, MP-BF exploits the advantages of splitting the demands of multi-path routing, but it reduces the average number of splits needed when compared with other multi-path approaches. Therefore, EONs can carry 25% more traffic when MP-BF is used for solving the RMSA problem instead of using other previous proposals from the literature. Moreover, the efficient splitting of the demands also translates into energy savings of up to 36% when compared with the other multi-path strategies.

Future work includes extending the algorithm to support constraints on the maximum differential delay between paths and analyzing its performance and impact on fragmentation of the spectrum in different topologies and service level agreement schemes. The extension to a different environment like space division multiplexing (SDM) elastic optical networks is also an interesting future research line.

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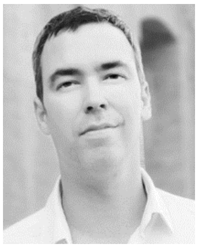

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