Received 2 September 2024, accepted 28 September 2024, date of publication 3 October 2024, date of current version 15 October 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3472651

TOPICAL REVIEW

Algorithms for Routing and Spectrum Allocation in Elastic Optical Networks: A Taxonomy

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This work was supported in part by Conacyt Paraguay Project POSG17-53; and in part by the Facultad Politécnica, Universidad Nacional de Asunción (FP-UNA), through the Research Projects Fund under Grant 1117/2023.

ABSTRACT Elastic Optical Networks (EONs) increase the transport capacity of standard optical networks, and have been proposed as a short-term solution to satisfy the dynamic demands of service quality requirements. To this end, the development of algorithms to better facilitate Routing and Spectrum Allocation (RSA) is envisaged to have a critical impact on the performance of EON. Given the abundance of RSA algorithms, this study presents the unique challenge of organizing and classifying them meaningfully to understand and select the most suitable approach for the corresponding niche service quality requirements. This study proposes a novel taxonomy structure for grouping RSA algorithms based on the following criteria: (1) resource assignment policies, (2) flexibility type, (3) traffic type, (4) optimization approaches, (5) number of objective functions, and (6) problem separability. Finally, the contributions of this study are twofold: it presents a state-of-the-art taxonomy framework that organizes existing published works based on a set of predetermined criteria, and explores research opportunities involving RSA algorithms to realize the full potential of EONs in telecommunications.

INDEX TERMS Classification criteria, elastic optical networks, routing and spectrum allocation, taxonomy.

I. INTRODUCTION

The continued demand growth for bandwidth in telecommunications networks, fueled by services such Video-On-Demand and streaming, is making the optical networks already deployed face capacity saturation.

Elastic Optical Networks (EONs) arise as a short and medium-term solution since they increase optical network capacity as stated by López and Velasco [1].

According to [1], EONs combine different modulation techniques, conversion of electrical to optical signals, circuit switching of optical signals, and spectrum resource management algorithms.

Jinno et al. [2] first proposed EON technology. These authors named their proposal Spectrum-sLICed Elastic optical path network (SLICE) [3].

Jinno et al. [2] stated that increased EON capacity can be achieved by optimizing the use of the available wavelength spectrum for signal transmission over an optical fiber. This optimization is mainly owing to two technological aspects: (1) a reduction in the size of the minimum effective frequency slot, and (2) the possibility of change (increase or decrease) of the slot width of the effective frequency slot according to the requested bandwidth.

Chatteryee et al. [4] stated that, in optical networks, the Optical Path (OP) is the route through which information travels within an optical network from a source to a destination node. In some studies [5], [6], [7], the term light path was also used to refer to the OP, while in [8] the equivalent term is media channel.

The terms Elastic or Flexible indicate that EON allows variation in bandwidth and bit rate among different OPs, and both terms will be used interchangeably. Gerstel et al. [9] stated that this extended concept is called Elastic Optical Path (EOP). Thus, an EON is an optical network that allows flexible optical paths.

Several technologies are required for an EON to build each EOP, including spectrum allocation and routing mechanisms.

The associate editor coordinating the review of this manuscript and approving it for publication was Tianhua Xu.

Zhang et al. [10] named this problem Routing and Spectrum Allocation (RSA), and it is considered the central problem in the resource management of EON because other resource management challenges are just generalizations of the RSA problem.

Algorithms that solve the RSA problem have a critical impact on EON performance [4]. Several studies have focused on this problem from various perspectives. Therefore, there is a need to understand the interaction, limitations, and scope of these proposals to determine the aspects that have already been solved and to visualize those that have not yet been addressed in the literature.

A. CONTRIBUTIONS

Studies [4], [11], [12], and [13] have presented different classifications of the RSA problem. Table 1 presents a summary of reviews addressing the RSA problem. As shown in Table 1, various published papers have covered different topics related to EON. In contrast, a novel taxonomy of algorithms used to solve the RSA problem is proposed in this study. Therefore, the first step is to classify the RSA problem by considering different criteria.

To the best of our knowledge, no other paper in the literature presents a complete taxonomy along with the combination of classification criteria that we present for RSA algorithms in EON.

B. SCOPE

RSA algorithms for transparent EON, that is, EON without optical-electrical-optical conversion, are the scope of this work. It should be mentioned that this study does not consider the following topics: spatial division multiplexing [15], survivability [4], fragmentation management [16], optical grooming [17], [18], Quality of Transmission-aware (QoT-aware) [19], [20], Impairment Aware-Routing, Modulation Level, and Spectrum Allocation (IA-RMLSA) [21], [22]. Interested readers can find additional information in the cited literature.

C. ARTICLE STRUCTURE

The remainder of this paper is organized as follows: Section II defines the classification criteria, and Sections III to VIII develop different criteria. Section IX presents the proposed taxonomy and Section X discusses the results. Finally, Section XI concludes the study and suggests future research directions.

II. RSA CLASSIFICATION CRITERIA

The goal of RSA algorithms is to allocate optical resources efficiently so that connection requests arriving from an origin can reach a destination within the network [11].

Given the large number of RSA algorithms, we searched for a method to characterize them. The authors of [4], [10], and [14] presented relevant classification alternatives for these algorithms, of which we selected six characteristics that differentiated the algorithms from each other, thereby proposing a novel taxonomy of RSA algorithms. The selected characteristics are as follows:

1) resources assignment policies,
2) flexibility type,
3) traffic type,
4) optimization approaches,
5) number of objective functions, and
6) problem separability.

Before starting, we need some definitions

- A frequency grid is defined as a set of reference frequencies used in optical networks [23].
- The Frequency Slot (FS) is the range of contiguous frequencies assigned to a slot of a flexible grid. A Central Frequency (CF) and spectral slot width characterize a FS [23].
- The Spectral Slot Width is the total width of the frequency slots in a flexible grid [23].
- A Media channel is a straightforward concept in the context of optical networks. It is simply an association of media that represents both the path through the media and the frequency slot it occupies [8].
- *"The effective frequency slot of a media channel is the frequency range common to the frequency slots of the filter functions present in the media channel. It is described by its nominal central frequency and its slot width" [8].*
- An Optical Tributary Signal (OTSi) is an important component of an optical network. It's an optical signal that is placed within a network media channel for transport across the optical network. This signal can consist of a single modulated optical carrier or a group of modulated optical carriers or subcarriers [24].
- The Optical Tributary Signal Group (OTSiG) *"is the set of optical tributary signals (OTSi) that supports a single digital client"* [8].

We include the following definitions for pedagogical purposes because although, according to ITU-T recommendations, a FS has a slot width of variable size, in most papers that work with RSA [3], [20], [25], [26], [27], [28], it is considered that one FS has a fixed slot width equal to the smallest possible value and that these FS are grouped contiguously to have enough bandwidth for the amount of information to be transmitted.

- When the center frequencies are indexed, we simply refer to them as the indices.
- The Slot Block is a set of contiguous slots where each slot width is minimum, typically 12.5 Gbps, equivalent to the slot width.

III. RESOURCES ASSIGNMENT POLICIES

The main task of the RSA algorithm is to choose the route and slot block to be assigned to a given request; that is, the algorithm calculates and assigns an EOP to carry traffic from one point to another in an EON. As explained in [4], the RSA problem is a combination of two problems: (1) route allocation and (2) spectrum allocation.

TABLE 1. Summary of review papers on the RSA problem.

Reference	Main subject	Year
[14]	Describes the performance, cost, energy efficiency and control plane requirements of EON.	2012
[10]	Describes the modulation format and early transmission systems for EON. Mentions technological aspects of physical layer; discusses network optimization involving spectrum fragmentation concepts, types of RSA, costs in EON, the grooming concept and the control plane.	2012
[9]	Describes the drivers, building blocks, architecture, and technologies that make EON possible, as well as early standardization efforts.	2012
[11]	Reviews and classifies spectrum management techniques for EON, without performing analysis of mentioned techniques.	2014
[4]	Reviews and classifies RSA approach, introduces basic EON concepts, network and node models. Describes fragmentation and defragmentation in RSA and mentions energy efficiency in EON.	2015
[12]	Reviews aspects of spectral and spatial flexibility in EON Discusses benefits of network flexibility for telecommunications.	2015
[1]	Presents the evolution of early optical networks to EON, describes the applications that EON can support, and network planning. Discusses the advances in transmission methods and node architecture. Describes the control plane and techniques employed in that plane.	2016
[13]	Performs a study, classification, analysis and comparison of RSA algorithms with and without modulation adjustment in aspects of quality, performance and computational complexity.	2017
This work	Selects six relevant criteria of RSA algorithms and based on these criteria makes a taxonomy of RSA algorithms.	2024

A. ROUTE ALLOCATION POLICIES

It is worth mentioning that the routing problem is inherited from traditional communication networks. Route allocation policies determine the network links or optical fibers that establish a route from a source to a destination node. According to Talebi et al. [11], there are two types of route allocation policy: single-path and multi-path schemes.

1) SINGLE PATH SCHEME

In this scheme, algorithms assign a single path that carries the full traffic volume of a request from the source node to the destination node. Within this scheme, Chatterjee et al. [4] classified a single path as fixed, fixed alternate, or adaptive routing.

a: FIXED ROUTING

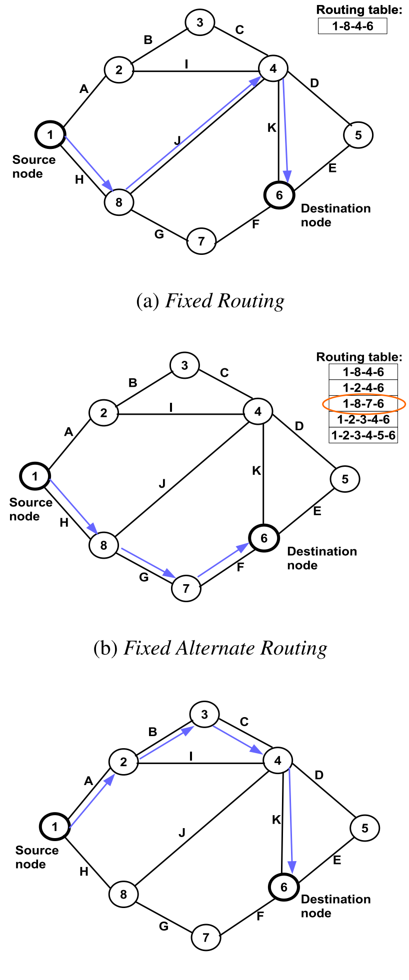
Figure 1a shows a single fixed-route example. In this scheme, a route is pre-computed for each source-destination pair. The RSA problem was simplified to a spectrum-allocation problem. Regardless of the network state, the algorithm only has to decide which slot block to assign to the pre-computed route to establish an EOP. This scheme is still used in the literature, although we found only two recent papers that use it [21], [29], which may indicate that this scheme is losing relevance.

b: FIXED ALTERNATE ROUTING

In this scheme, each node in the network maintains a pre-computed routing table that contains an ordered list of a fixed number of routes to all the other nodes. The algorithms select only one route to carry the traffic according to the network state, as shown in Figure 1b. This is the routing method most commonly found in the literature, as can be seen in Tables 3 and 4, of which several papers are recent [16], [21], [25], [28], [30], [31], [32], [33], [34], [35].

c: ADAPTIVE ROUTING

This scheme dynamically chooses routes according to network status, as shown in Figure 1c. It should be noted that a pre-computed routing table is not necessary because all possible routes are candidates. The adaptive routing algorithm attempts to satisfy requests sequentially, based on the network state.

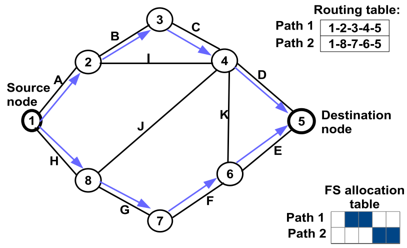


(a) *Fixed Routing*

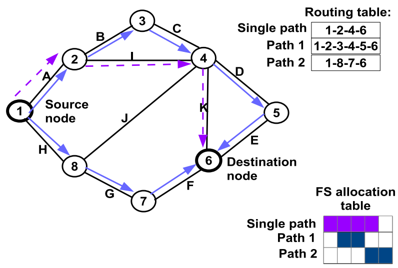
(b) *Fixed Alternate Routing*

(c) *Adaptive Routing*

FIGURE 1. Route allocation policies, (1a) fixed routing, (1b) fixed alternate routing, (1c) adaptive routing.



(a) *Multi-path Routing*



(b) *Hybrid Single Multi-path Routing*

FIGURE 2. Route allocation policies, (2a) multi-path routing, and (2b) hybrid routing.

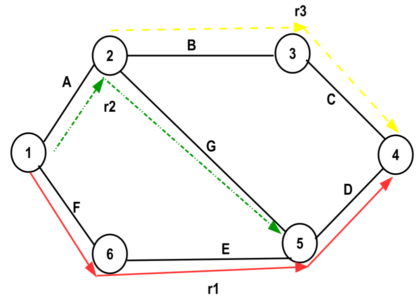
2) MULTI-PATH SCHEME

As explained in [4] and [11], multi-path based algorithms seek to calculate a set of routes that jointly carry all the traffic volume for each request in such a way that each route carries a portion of traffic. Thus, the traffic flow is divided at the source node and merged at the destination node using synchronization algorithms, as shown in Figure 2a. Zhu et al. [36] stated that this scheme presents several challenges, such as minimizing the number of paths and the difference in routing delays.

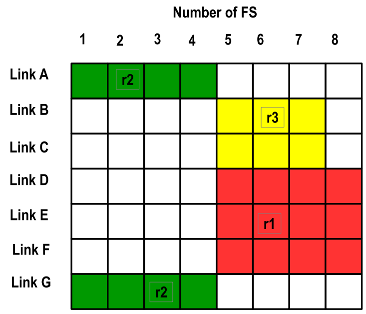
The proposal of Jinno et al. [2] avoids multi-path routing to reduce the cost of electronic processing that multi-path routing requires. According to Din et al. [37], serving certain high-bandwidth requests with single-path routing is difficult under bandwidth constraints. Therefore, relying on multi-path routing can reduce the likelihood of network congestion. Multiple paths help handle request fragmentation by not requiring all bandwidth to be routed through a single path [4].

3) HYBRID SCHEME

In this scheme, the algorithm first attempts to allocate all the traffic to a single path. If sufficient resources are unavailable, traffic is split into multiple sub-traffic. The sub-traffic is carried by different paths to minimize the blocking probability and maximize the spectral efficiency. The transmission parameters depend on the required transparent reach or maximum transmission distance of a single-core optical-amplified fiber. However, this scheme increases the number of transponders [37]. Figure 2b shows an example of this policy; the single path case is shown by dashed lines, and the multi-path alternative is shown as solid lines.



(a) Routing for source-destination pairs $r1 = (1, 4)$, $r2 = (1, 5)$, $r3 = (2, 4)$



(b) Slot block allocation for each request

FIGURE 3. A simple example of communication establishment in EON.

B. SPECTRUM ALLOCATION POLICIES

Spectrum allocation policies determine the size of the slot blocks granted to the connection request; each assignment satisfies continuity, contiguity, and non-overlapping constraints [38], [39].

Figure 3 shows an example of communication establishment in an EON. Figure 3a shows a network with nodes numbered 1 to 6 and links labeled A to G. The arrows indicate routes in which all links support eight FSs. At the same time, Figure 3b shows a spectrum allocation for each request considered; each spectrum allocation meets continuity, contiguity, and non-overlapping constraints.

Typically, the slot block to be assigned is defined as a function of requested bandwidth, network state, and route. According to [4], spectrum allocation policies can be classified into (a) spectrum allocation to individual requests and (b) spectrum allocation by connection groups.

1) SPECTRUM ALLOCATION TO INDIVIDUAL REQUESTS

Chatterjee et al. [4] explained that, in this scheme, the algorithms calculate and assign the slot block to each route sequentially. There is a wide variety of policies for assigning spectra to individual requests. In this study, we cited some of the most commonly used methods.

a: FIRST-FIT ALLOCATION

From the list of indexed slot blocks, the slot block with the lowest available CF was selected for assignment to the optical path that served the connection request. This policy is considered one of the best options because of its low blocking probability and low computational complexity [40].

b: OTHERS

In addition to the first-fit, there is a large variety of schemes for spectrum allocation to individual requests, of which we only cite the most used after the first-fit. Each scheme is cited by the name under which it was published for the first time:

- Random fit: An available slot block is randomly selected for assignment [40].
- Best fit: An available slot block that exactly fits the required bandwidth request is selected for assignment [41].
- Bit-rate aware: This sorts requests from the highest to lowest transmission data rates and then allocates slot blocks using a first-fit strategy [41].
- Last fit [42]: This chooses a slot block with the highest center frequency from the list of available slots to be assigned to the optical path that will serve the connection request.
- Least-Used [43]: From the list of available slot blocks, the least-used slots on the fiber links of the network are chosen. If several available FSs share the same minimum usage level, then a first-fit policy is used to select the FS to be used. This policy was employed to evenly spread the load across all the spectral slots.
- First-Last fit [44]: All FSs of each link are divided into a certain number of partitions, and the lower CF slots are chosen in the odd-numbered partition, whereas for the even-numbered partitions, the higher CF slots are chosen from the list of available slots. Compared to the random fit and first-fit strategies, this approach achieves a more adjacent FS. For example, in a link with eight FSs, $f_1, f_2, f_3, \ldots, f_8$, this scheme is divided into two sets: Odd(f_1, f_3, f_5, f_7) and Even(f_2, f_4, f_6, f_8); the first element it selects from Odd is f_1 and the first element it selects from the Even set is f_8, and so on.
- Most used [43]: This policy selects the FSs used by most fiber links in the network. If several FSs share the same maximum usage level, a first-fit policy is used to break ties. This policy is used to achieve the maximum spectrum reuse of the network.
- Exact fit [40]: This assigns a spectrum if it finds a slot block with the exact size of requested resources. If an exact slot block is not found, then the first-fit policy is used. This spectrum allocation policy seeks to reduce fragmentation problems.
- Best Fit [41]: It allocates a slot block that has exactly the required size for each connection request; if there is no slot block that fits the requested spectrum, the algorithm allocates a slot block with the closest sufficient size to that of the connection request.
- MSCL (Min Slot-continuity Capacity Loss) [45]: Among all FSs available to be assigned to a request, this policy assigns FSs that provide the least capacity loss according to a pre-established network capacity rule.

Each scheme presented here has an advantage over first-fit but at the cost of computational time and implementation complexity.

2) SPECTRUM ALLOCATION BY CONNECTION GROUPS

In this type of spectrum allocation, FSs are grouped in a range around an index, according to the size of the connection request. There are three possible cases: (1) fixed spectrum allocation, (2) semi-elastic spectrum allocation, and (3) elastic spectrum allocation [4].

Fixed spectrum allocation operates as allocation to individual requests seen in III-B1, that is, after the slot blocks are assigned, CF and the number of FS of the slot block remain unchanged during the duration of the communication, as shown in Figure 4a. However, both semi-elastic and elastic spectrum allocations use time-varying traffic, as explained in [4] and [46].

Xu et al. [46] stated that time-varying traffic allows the assigned FSs to two or more contiguous requests to increase or decrease around the index, as long as the frequency varies within a reasonable range and guard band, and the FS does not overlap.

a: FIXED SPECTRUM ALLOCATION

Both the index and size of the slot block remained static for the entire network operation time, as shown in Figure 4a.

b: SEMI-ELASTIC SPECTRUM ALLOCATION

The index of the slot block remained fixed; however, its size varies at different time intervals, as shown in Figure 4b.

c: ELASTIC SPECTRUM ALLOCATION

Both the index and size of the slot block can change at each time interval, as shown in Figure 4c.

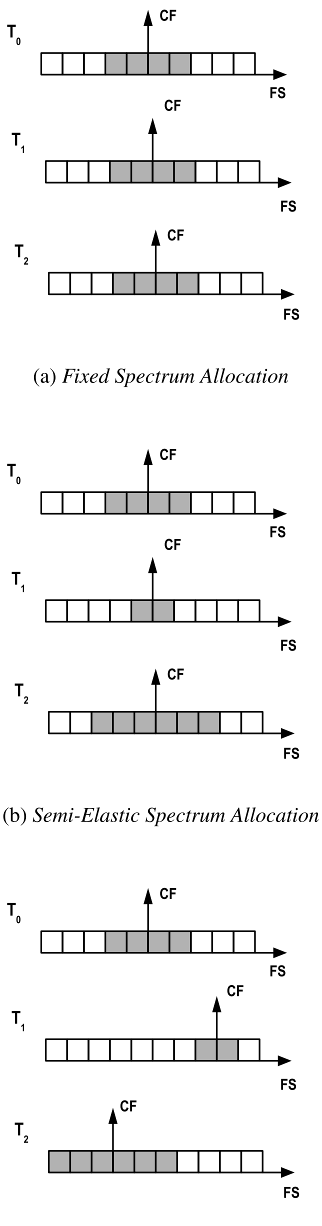
IV. FLEXIBILITY TYPE

Several authors, such as Gerstel et al. [9], Tomkos et al. [14], Xia et al. [12], and Proietti et al. [47], have examined the notion of flexibility in EON.

Gerstel et al. [9] studied two degrees of elasticity: first, the capability of varying the bandwidth available for information transmission and second, the capability of tuning the data transmission rate of the signal.

According to Tomkos et al. [14], flexibility in optical networks is the ability to dynamically adjust available resources such as wavelength channels, bandwidth, transmission format, and data rate.

The flexibility concepts in [9] and [14] were further developed in [12] and [47]. According to Xia et al. [12],



(a) *Fixed Spectrum Allocation*

(b) *Semi-Elastic Spectrum Allocation*

(c) *Elastic Spectrum Allocation*

FIGURE 4. **Spectrum allocation by connection groups.**

adding flexibility to the optical layer is a key step in increasing network efficiency. Proietti et al. [47] divided the physical domain into three, where flexibility could be implemented.

1) *Time domain*: modulation type and symbol rate of the signal can vary;
2) *Frequency domain*: wavelength of signal could be manipulated;
3) *Spatial domain*: The system may have single- or multiple-mode optical fibers, multi-core fibers, and different light polarization modes.

On the other hand, Xia et al. [12] proposes a different classification of flexibility than the one proposed by Proietti et al. [47]:

1) Spatial flexibility and,
2) Spectral flexibility.

This study uses the definition of flexibility given by [12] owing to its generality. We will focus on spectral flexibility, leaving spatial flexibility to future work. Following [12], within the spectral flexibility, this study considers four cases, as explained in the following four sub-sections.

A. FLEXIBILITY IN CHANNEL GRID, BANDWIDTH AND OVERHEAD

The index and size of a slot block can vary depending on the transmission request data rate, symbol rate, channel layout in the spectrum and header [37], [48], [49].

B. FLEXIBILITY IN MODULATION FORMAT

Optical systems can achieve a longer transmission distance with a trade-off in data rate by varying the modulation format [38], [50]. The modulation formats found in articles discussing RSA in EON are Quadrature Phase-Shift Keying (QPSK), Binary Phase-Shift Keying (BPSK), Quadrature Amplitude Modulation (m-QAM), where *m* can be 8, 16, 32, or 64 [11], [50], [51].

Other modulation formats used in optical networks are QAM formats with variable code rate, hybrid time-domain formats, probabilistic constellation shaping [52], dual-polarization [53], single side-band with carrier suppression [54], and polarization division multiplexing (PDM)-BPSK, PDM-QPSK, as well as PDM-mQAM, where *m* can take values of 8, 16, 32, 64, 128, or 256 [51], [52].

C. FLEXIBILITY IN THE NUMBER OF SUPER-CHANNEL CARRIERS

As mentioned earlier, the union of several FSs results in the formation of a slot block capable of dealing with more data than one FS alone without adding more transceivers. This union of many FSs is a slot block, known as a super-channel when it exceeds the size of a standard DWDM channel, i.e., when the slot block width exceeds 12.5 GHz, 25 GHz, 50 GHz, or 100 GHz [2], [12], [50]. The super-channel is called a flexible grid in [23].

D. FLEXIBILITY IN WORKING OPTICAL BAND

The use of new technologies allows the selection of different transceivers, thereby increasing the available frequencies for sending desired information, as explained in [12] and [49].

An additional advantage of EON is that the migration from a fixed grid to a flexible grid can be done gradually using transceivers of different grid types [55].

Dallaglio et al. [56] explores the impact of using two types of Sliceable Bandwidth Variable Transponders (SBVT) in EON:

- Multi Laser-Sliceable Bandwidth Variable Transponders (ML-SBVTs) use independent tunable lasers for each subcarrier.

- Multi Wavelength-Sliceable Bandwidth Variable Transponders (MW-SBVTs) that use a single laser to generate multiple subcarriers.

In a later study, Dallaglio et al. [5] presented the Routing, Spectrum, and Transponder Assignment (RSTA) algorithm, which combines both ML-SBVT and MW-SBVT technologies into a single EON to achieve the best characteristics of each technology in the network.

To use RSTA, the EON must have nodes with a set of ML-SBVTs and MW-SBVTs. The RSTA algorithm integrates dynamic transponder selection with route and spectrum allocation for each connection request [5].

Masood et al. [57] proposed a transponder-selection model for an EON during the planning stage. In the proposed model, the dedicated transponder options are the ML-SBVT and MW-SBVT as well as the Flex-OCSM centralized transponder option proposed in [58]. The model indicates the number and type of transponders assigned to a node according to traffic simulation. The model also assumes that the Lightpath and Spectrum Mapping for SBVTs (LSM-SBVT) orchestration algorithm is used in the control layer [57].

V. TRAFFIC TYPE

Traffic models describe the behavior of traffic handled by a network, reflecting the needs of network operators and the capabilities of available technologies, as explained in [59], [60], [61], and [62].

According to [59], [60], and [61], RSA algorithms developed for one traffic model may not necessarily handle other types of traffic. Thus, the type of traffic handled by the algorithm was a differentiating factor.

This study analyzed three types of traffic: (1) dynamic, (2) static, and (3) advance reservation. The literature includes other types of traffic, but references are scarce. In this work we classify incremental traffic [63], multi-period traffic [64], and variable over time traffic [65] as dynamic traffic.

A. DYNAMIC TRAFFIC

In this scenario, traffic demands arrive randomly and last for a random amount of time [59], [60]. A particular case is incremental traffic, where connection requests arrive sequentially and last for an indefinite period of time, as stated in [60].

B. STATIC TRAFFIC

Charbonneau et al. [62] explained that in static traffic, the entire set of connection requests is known in advance and used in network planning.

C. ADVANCE RESERVATION

In advance reservation, traffic can be transmitted after it is received, and the connection duration is known or can be calculated. This type of traffic considers four cases, as stated in [62] and [66]:

1) *Starting Time Specify Duration* (STSD): Demands specifying start time and duration time
2) *Starting Time Unspecified Duration* (STUD): demands that specify the start time, but not the duration time
3) *Unspecified Time Specified Duration* (UTSD): demands that specify the duration but not the start time
4) *Unspecified Starting Time and Unspecified Duration* (UTUD): Demands that do not specify the start time or communication duration.

VI. OPTIMIZATION APPROACHES

The RSA problem can be regarded as an optimization problem in which the goal is to determine a route and spectrum subject to continuity, contiguity, and non-overlapping constraints. The RSA problem involves one or more objective functions (see [1], [14]).

Optimization approaches are available to solve the RSA problem. The number of objective functions is discussed in the following subsection.

The optimization approach can be divided into four large groups: (1) mathematical optimization, (2) heuristics, (3) meta-heuristics, and (4) machine learning [1], [14], [67].

A. MATHEMATICAL OPTIMIZATION

Mathematical optimization uses exact methods to perform optimization. The results obtained are optimal; however, they have a high computational cost because RSA is an NP-hard problem, as stated by [4] and [68].

In this group, we determine the RSA based on Integer Linear Programming (ILP) or Mixed Integer Linear Programming (MILP) [14], [26].

Linear programming seeks to optimize a linear objective function subject to linear constraints. ILP is a linear program in which the solution components must be integers, while MILP is a linear program in which not all the solution components must be integers [69].

B. HEURISTICS

Hillier and Lieberman [68] explained that a heuristic method can find good, but not necessarily optimal solutions for a specific problem under consideration. These methods are used when the problem is very complicated and an optimal solution is difficult to achieve using other methods in a reasonable time. The vast majority of heuristics are stochastic because the generation of solutions is aleatory [70].

A complete and detailed study of the various heuristics available in literature is beyond the scope of this study. In this sub-section, we briefly summarize these observed cases.

The following studies presented new routing heuristics combined with spectrum allocation algorithms available in the literature: [71] used a routing engine along with a first-fit. [72] proposes an adaptive routing approach using a relative cost formula and a first-fit for spectrum allocation. Brasileiro et al. [73] proposed an algorithm based on fuzzy logic for routing and first-fit for spectrum allocation.

The following papers present spectrum allocation algorithms combined with routing algorithms available in the literature: Olszewski [74] proposed a combination of fixed alternate routing and modified first-fit for both routing and spectrum allocation. Khan [35] proposed a fixed alternate routing and a spectrum allocation algorithm called first-last-mixed-fit. Zhao et al. [75] proposed a heuristic that combines adaptive routing with highest-modulation-first last-fit spectrum allocation. Yuan et al. [76] used adaptive routing and proposed minimizing the sum of the weighted resource reductions for spectrum allocation.

The following studies proposed new heuristics to solve both routing and spectrum allocation problems. Bermudez et al. [77] solved the RMLSA problem in two steps: first, they used an algorithm called Least Demand Bandwidth Balance (LDBB) for the route and modulation level (RML), and in the case of spectrum allocation, they proposed two options: sliding-fit (SF) and parcel-fit (PF). Tang et al. [18] proposed a heuristic algorithm based on auxiliary graphs, and Moura et al. [78] proposed an Energy Aware Multigraph Shortest Path (EAMGSP) algorithm to solve the RMLSA problem considering the energy consumption of the network elements. Moura et al. [79] proposed the Multigraph Shortest Path algorithm.

The following papers propose heuristics that address related problems and solve them together with the RSA, Yadav et al. [80] proposes the Quasi Path Restoration (QPR) heuristic that divides the available spectrum into two, primary spectrum and backup spectrum, using adaptive routing and first-fit. Dharmaweera et al. [81] presented a heuristic to solve the RMSA problem by considering the imperfections of the optical fiber by combining adaptive routing and first-fit. Yin et al. [82] proposed two heuristics, fragmentation-aware (FA) and FA with congestion avoidance (FA-CA) RSA, both of which solve the RSA problem and use adaptive routing with a first-fit. Xu et al. [83] proposed a heuristic that first computes the k-shortest paths and then uses a fragmentation-aware spectrum allocation algorithm.

Agrawal et al. [84] proposed a heuristic that efficiently provides service-level agreement (SLA), called SLA-aware differentiated QoS (SADQ), which uses service differentiation at the routing level, spectrum allocation, and link resilience. Ji et al. [85] presented a set of heuristics that solved the RSA problem for network planning, and employed a pre-configured-cycle (p-cycle).

Beyranvand et al. [86] presented a heuristic that considers the quality of transmission in a network, called quality-of-transmission (QoT)-aware dynamic routing, modulation level, and spectrum assignment (QoT-aware RSA). Fontinele et al. [22] proposed an algorithm that considers the effects of physical layer imperfections when solving the RMLSA problem. Ibrahimi et al. [20] used machine learning (ML) to estimate the parameters that affect the transmission quality in an EON, and the estimated data were used as input parameters for the heuristic that solves the RSA problem. Fernandez et al. [16] proposed a proactive-reactive based approach defragmentation algorithm.

C. META-HEURISTICS

Meta-heuristics are high-level strategies that guide the heuristics of a specific problem to improve its performance [27]. Owing to their non-deterministic nature, meta-heuristics cannot guarantee the attainment of an optimal solution [87].

Ezugwu et al. [87] presented a meta-heuristic classification. Melian et al. [88] proposed a simple classification method. For our purposes, we used the classification proposed by Melian et al.

- Relaxation meta-heuristics: To solve a problem, models that describe the problem are generally used. Relaxation meta-heuristics are techniques that help simplify models such that they are easier to solve, and the solutions have an acceptable approximation to the optimal solutions.
- Constructive meta-heuristics: These establish strategies to construct a good solution to the problem step-by-step. An example of constructive meta-heuristics is the greedy strategy [88].
- Search meta-heuristics: These establish strategies to guide heuristics in traversing the solution space and iteratively transforming the starting solutions to improve the search for new solutions.
- Evolutionary meta-heuristics: Similar to search meta-heuristics. The difference is that there is an interaction among the solutions (called a population in evolutionary meta-heuristics), which allows the traversal of the solution space, as opposed to the individual modifications of the starting solutions in search meta-heuristics. The difference between search and evolutionary meta-heuristics is that search meta-heuristics use systematic procedures, whereas evolutionary meta-heuristics use random approaches [88].

D. MACHINE LEARNING

Zhang et al. [67] presented a review of Machine Learning used in RSA for optical networks. According to the authors, ML offers advantages in solving complex problems such as extracting significant information from historical data and making relevant decisions for the correct functioning of a system based on network-generated data.

In optical networks [67], the types of ML used are Logistic Regression (LR), Random Forest (RF), clustering, Q-learning, Deep Reinforcement Learning (DRL) [89] and Deep Neural Networks (DNN).

- LR is a generalization of a linear regression analysis model, which is a classification technique.
- RF integrates many Decision Trees (DT) through Ensemble Learning and is used for classification and regression problems.
- Q-learning is a value-based technique for Reinforcement Learning (RL). RL typically involves two entities: an agent and an environment.

- DRL consists of an agent interacting with an environment. Using a DNN, the agent learns how to act to maximize its reward [90].
- A DNN, also known as a multi-layer perceptron (MPL), is a neural network with many hidden layers.

DNN and Q-learning have been applied to routing, RMSA, and RSA problems [67].

VII. NUMBER OF OBJECTIVE FUNCTIONS

Chong and Zak [69] classified RSA algorithms based on the number of objective functions considered for optimization: (1) single-objective optimization and (2) multi-objective optimization. Von Lucken et al. [91] also considered a third group called (3) many-objective optimization.

A. SINGLE-OBJECTIVE OPTIMIZATION

Single-objective optimization considers only one objective function to guide the optimization process [69]. This approach is by far the most common in specialized literature, as can be seen in Tables 3 and 4.

B. MULTI-OBJECTIVE OPTIMIZATION

Multi-objective optimization considers more than one objective function, typically 2 or 3. If these objective functions conflict, the goal is to determine a set of trade-off solutions known as the Pareto set [91].

In the minimization context, a point is a Pareto minimizer or non-dominated solution if there is no other possible decision variable that can decrease any objective function without causing simultaneous increases in any other objective function. The set of Pareto minimizers or Pareto optimizers is called a Pareto set, and its image in the objective space is known as the Pareto front [91].

According to [69] we can obtain two cases of multi-objective optimizers:

1) Pareto front-based techniques: This technique presents the entire Pareto front as a solution or a good approximation.
2) Trade-off solution-based techniques: This technique typically presents only one point of the Pareto front [34], [69].

C. MANY-OBJECTIVE OPTIMIZATION

A many-objective optimization problem is a multi-objective optimization problem which considers many conflicting objective functions, typically more than three as explained in [91].

This distinction between multi-objective and many-objective optimization is necessary because, from four or more objective functions, multi-objective methods have convergence problems. The increased number of objective functions makes it difficult to discriminate between solutions using only the dominant relation between them. Consequently, many-objective optimization approaches emerge as a promissory alternative [91].

VIII. PROBLEM SEPARABILITY

According to [4], the RSA problem can be solved in two ways: (1) by solving the problem jointly (*Joint RSA*), Zhang et al. [10] called this approach one step; or (2) dividing the RSA problem into two sub-problems: the routing sub-problem (or routing and modulation level) and the spectrum allocation sub-problem, $R + SA$, (separate RSA), [10], [26], which is a two-step approach.

A. JOINT RSA

This approach is more computationally expensive than the separate RSA approach; however, it is more intuitive when implemented. It is particularly useful for small problems with ILP implementations, as discussed in [1], [4], [11], and [25].

B. SEPARATE RSA

Algorithms that solve the RSA problem by dividing it into sub-problems are less complex than joint RSA algorithms [10]. In this approach, the Routing (R) sub-problem is typically solved first, followed by the Spectrum Allocation (SA) sub-problem. Both the R and the SA sub-problems are solved separately and sequentially [1], [4], [10], [11].

Dinarte et al. [28] analyzed the effect of changing the solution order of the R and SA sub-problems. The authors presented a Hybrid Routing and Spectrum Assignment (HRSA) algorithm.

The HRSA is a genetic algorithm-based meta-heuristic that uses an ordering approach to choose between $R + SA$ and $SA+R$ strategies; that is, HRSA chooses between performing spectrum allocation based on a route ($R+SA$) or routing based on some spectrum allocation criteria ($SA + R$). HRSA selects one strategy for each source-destination pair, and the selected strategy is the one with the lowest blocking probability for the source-destination pair [28].

According to [28], $R+SA$ prioritizes routing strategies that can be routed with shorter distances or fewer hops. $SA + R$ prioritizes load-balancing and spectrum orchestration.

IX. TAXONOMY OF RSA ALGORITHMS

We constructed a taxonomy based on these six classifications. Table 2 summarizes this taxonomy and shows the percentage of consulted algorithms for each sub-classification.

Tables 3 and 4 list the 75 selected articles sorted by sub-classes. Not all studies related to RSA algorithms in EON were included in the 75 classified articles.

As seen in Table 2, there are 10 sub-classes for the classification criteria: (1) *resource assignment policies*, while the classification criteria (2) *flexibility type* considers four sub-classes. Criteria (3) *traffic type*, (4) *optimization approaches*, and (5) *number of objective functions* take into account 3 sub-classes each, while the last (6) *problem separability* criteria considers two sub-classes; therefore, there are $10 \times 4 \times 3 \times 4 \times 3 \times 2 = 2880$ possible combinations. This is a large number to be presented in a single table, as shown in Tables 3 and 4.

TABLE 2. Taxonomy summary.

Resources assignment policies	Route allocation	Single path	Fixed routing (17%)	[21], [29], [40], [41], [41], [45], [71], [92], [93], [93], [93], [94], [94], [94], [94]–[97], [97], [97]
			Fixed alternate routing (38%)	[21], [22], [22], [30], [34], [35], [74], [83], [85], [85], [85], [86], [95], [98]–[102], [102], [103] [5], [16], [18], [18], [20], [28], [36]–[39], [49], [50], [96], [96], [104], [104], [104], [105], [105], [106] [25], [26], [31]–[33], [107]
			Adaptive routing (34%)	[36], [37], [37], [37], [57], [61], [72], [73], [75], [78]–[82], [82], [86], [94], [108]–[110] [26], [27], [27], [76], [77], [84], [111]–[113], [113], [113]–[123]
		Multi-path (11%)		[5], [26], [26], [26], [37], [37], [37], [116], [124], [124], [124]–[126]
		Hybrid single and multi-path (8%)		[5], [32], [36], [36], [37], [37], [37], [99], [114]
	Spectrum allocation	Individual request	First-Fit (54%)	[21], [22], [72], [74], [80], [81], [85], [85], [85], [94], [94], [94], [94], [94], [95], [95], [98], [102], [103], [109] [16], [18], [18], [21], [28], [36], [36], [71], [73], [82], [82], [96], [96], [96], [104], [104], [104], [105], [105], [125] [5], [5], [5], [27], [27], [37], [37], [37], [37]–[39], [50], [57], [84], [111], [113], [113], [113], [115], [126] [107], [118], [120], [122], [123]
			Others (39%)	[22], [30], [34], [35], [74], [75], [78], [79], [83], [86], [86], [92], [93], [93], [93], [99]–[102], [108] [20], [25], [26], [26], [31], [32], [40], [41], [41], [45], [49], [61], [76], [77], [106], [110], [112], [114], [116], [117] [26], [26], [26], [29], [33], [119], [121]
		Group connections	Fixed (96%)	[30], [34], [35], [74], [75], [78], [79], [83], [85], [85], [85], [92], [98]–[102], [102], [103], [108] [18], [18], [20], [21], [21], [22], [22], [40], [72], [73], [80], [81], [86], [86], [93], [94], [94], [95], [95], [109] [16], [28], [45], [61], [71], [96], [96], [96], [97], [97], [97], [104], [104], [104], [110], [124], [124], [124], [127], [127] [5], [5], [5], [36], [36], [37], [37], [37], [37], [41], [41], [57], [82], [82], [105], [105], [106], [125], [127] [25], [27], [27], [31], [32], [38], [39], [49], [50], [76], [77], [84], [111]–[113], [113], [113]–[115], [126] [26], [26], [26], [26], [26], [29], [33], [107], [116]–[123]
			Semi-elastic (2%)	[93], [94]
			Elastic (3%)	[93], [94], [94]
Flexibility type	Channel grid, bandwidth and overhead (8%)			[27], [27], [37], [37], [37], [37], [49], [108], [111]
	Modulation format (62%)			[18], [18], [21], [21], [22], [22], [35], [75], [78], [80], [81], [86], [86], [98]–[102], [102], [108] [16], [36], [36], [71], [96], [96], [96], [97], [97], [97], [104], [104], [104], [106], [124], [124], [124], [127], [127], [127] [25], [27], [27], [32], [37], [37], [37], [37], [38], [49], [50], [76], [77], [113], [113], [113]–[116], [126] [26], [26], [26], [26], [26], [29], [33], [107], [118]–[123]
	Number of super channel carriers (100%)			[30], [34], [35], [74], [75], [78], [79], [83], [85], [85], [85], [92], [98]–[102], [102], [103], [108] [21], [21], [22], [22], [72], [80], [81], [86], [86], [93], [93], [93], [94], [94], [94], [94], [94], [95], [95], [109] [16], [18], [18], [20], [28], [40], [45], [61], [71], [73], [96], [96], [96], [97], [97], [97], [110], [124], [124], [124] [5], [5], [5], [36], [36], [41], [41], [57], [82], [82], [104], [104], [104], [105], [105], [106], [125], [127], [127], [127] [25], [27], [27], [31], [32], [37], [37], [37], [37]–[39], [49], [50], [76], [111]–[113], [113], [113], [114] [26], [26], [26], [26], [26], [29], [33], [77], [84], [107], [115]–[123], [126]
	Working optical band (4%)			[5], [5], [5], [57], [117]
Traffic type	Dynamic (62%)			[22], [34], [35], [72], [74], [75], [78]–[81], [83], [85], [85], [85], [86], [86], [98], [99], [108], [109] [16], [18], [20], [22], [28], [40], [41], [45], [61], [71], [73], [82], [82], [105], [105], [106], [110], [127], [127], [127] [5], [5], [5], [31], [32], [36], [36], [37], [37], [37], [38], [41], [49], [76], [111]–[113], [113], [113], [125] [29], [84], [107], [114]–[123], [126]
	Static (36%)			[18], [21], [21], [30], [92], [93], [93], [93], [94], [94], [94], [94], [94], [95], [95], [96], [96], [96], [97], [103] [25], [26], [26], [26], [27], [27], [31], [37], [39], [50], [57], [77], [97], [97], [104], [104], [104], [124], [124], [124] [26], [26], [33]
	Advance reservation (7%)			[31], [98]–[102], [102], [114]
Optimization approach	Mathematical optimization (18%)			[21], [25], [26], [26], [26], [26], [37], [39], [92], [94], [94], [94], [94]–[97], [97], [104], [124], [127] [26], [33]
	Heuristic (58%)			[35], [74], [75], [78], [79], [83], [85], [85], [85], [93], [93], [93], [98]–[102], [102], [108], [109] [16], [18], [18], [20]–[22], [22], [40], [45], [61], [72], [73], [80], [81], [86], [86], [95], [96], [96], [124] [5], [5], [5], [36], [36], [37], [37], [37], [41], [41], [49], [57], [71], [82], [82], [106], [111], [125], [127], [127] [32], [38], [76], [77], [84], [114]–[117]
	Meta-heuristic (16%)			[27], [27], [28], [30], [50], [94], [97], [103], [104], [104], [105], [105], [110], [112], [113], [113], [113], [124], [126]
	Machine Learning (8%)			[29], [31], [34], [107], [118]–[123]
Number of objective functions	Single-objective optimization (97%)			[35], [74], [75], [78], [79], [83], [85], [85], [85], [92], [93], [93], [93], [98]–[102], [102], [108] [18], [18], [20], [21], [21], [22], [22], [72], [80], [81], [86], [86], [94], [94], [94], [94], [94], [95], [95], [109] [16], [28], [40], [45], [61], [71], [73], [96], [96], [96], [97], [97], [97], [104], [104], [104], [110], [124], [124], [124] [5], [5], [5], [36], [36], [37], [37], [37], [41], [41], [57], [82], [82], [105], [105], [106], [125], [127], [127], [127] [25], [27], [27], [31], [32], [37]–[39], [49], [50], [76], [77], [84], [111]–[113], [113], [113]–[115] [26], [26], [26], [26], [26], [29], [33], [107], [116]–[123]
	Multi-objective optimization (3%)			[30], [34], [103], [126]
	Many-objective optimization (0%)			
Problem separability	Joint RSA (63%)			[21], [30], [35], [72], [78]–[80], [86], [92], [93], [93], [93], [95], [99], [100], [102], [102], [103], [108], [109] [16], [18], [18], [21], [61], [71], [82], [82], [96], [96], [96], [97], [97], [97], [104], [104], [104], [105], [105], [124] [5], [5], [5], [31], [32], [36], [36], [37], [37], [37], [37]–[39], [50], [111]–[113], [113], [113], [125] [27], [27], [29], [33], [76], [77], [84], [107], [114]–[116], [118]–[122]
	Separate RSA (30%)			[20], [22], [22], [28], [34], [40], [45], [73]–[75], [83], [85], [85], [85], [86], [95], [98], [101], [124], [124] [25], [26], [26], [26], [26], [26], [41], [41], [49], [57], [106], [110], [117], [119], [123], [126]

Thus, we removed the many-objective optimization columns because they had no entries, leaving a table showing $10 \times 4 \times 3 \times 4 \times 2 \times 2 = 1920$ possible combinations. Tables 3 and 4 present the taxonomy, where each cell indicates one of the 1920 possible sub-class combinations. The color of each cell indicates the number of algorithms found for each alternative combination: white cells indicate that there is no algorithm, green cells indicate that there are between 1 and 10 algorithms, yellow cells indicate that between 11 and 20 algorithms were found, and red cells indicate that 21 or more algorithms were found.

X. DISCUSSION

This section discusses the taxonomy presented in Tables 3 and 4, considering active research areas and opportunities.

A. ACTIVE RESEARCH AREAS

Among the routing policies, single-path policies are the most studied, with fixed alternate routing being by far the most used, followed by adaptive routing, while fixed routing is in third place. According to [115], fixed alternate routing outperforms fixed routing. However, adaptive routing with a clever strategy can improve both the strategies.

Concerning spectrum allocation policies, in the case of individual requests, the most used strategy was first-fit (54% of the studied occurrences). According to [109], this is because of the advantages of effectiveness and low computational cost offered by the first-fit approach.

Within the spectrum allocation strategies, individual requests classified as *Others* (39% of studied occurrences) include a variety of techniques, of which we cite the most used at the end of Subsection III-B1b.

For group connections (see Tables 3 and 4), the *fixed spectrum allocation strategy* was used most frequently, accounting for 96% of the studied occurrences. *Elastic* and *semi-elastic spectrum allocation* strategies, both with 2% and 3% of studied occurrences, respectively, require additional hardware to be implemented, thus increasing the complexity of the network according to [46] and [94]. This may explain why they are used less frequently than *fixed spectrum allocation*.

The most used types of flexibility are *the number of super-channel carriers* and *modulation format*, with 100% and 62% of the studied occurrences, respectively, because they do not require additional hardware to be implemented [5], [38], [49].

For the traffic type, there are a larger number of proposals studying dynamic traffic (62% of studied occurrences) than those considering static traffic and advance reservation, with 36% and 7% of studied occurrences, respectively. A greater use of dynamic traffic occurs because the main problem in EON is the management of the network in operation, with static traffic used mainly for planning the optical network, according to [59] and [62].

Regarding the optimization approach, mathematical optimization (18% of the studied occurrences), of which these papers used ILP [25], [26], [33], [37], [39], [92], [94], [95], [96], [97], [104], [124], [127], [128] and this MILP [21], [89], is mainly used to solve small problems that validate the idea, as stated in [1] and [14]. Thus, the authors of [1] and [4] argued that heuristic algorithms (58% of the studied occurrences) are used for realistic networks, mainly because they require less computational time despite providing non-optimal answers.

In the case of the number of objective functions, *single-objective optimization* was the most used, with 97% of

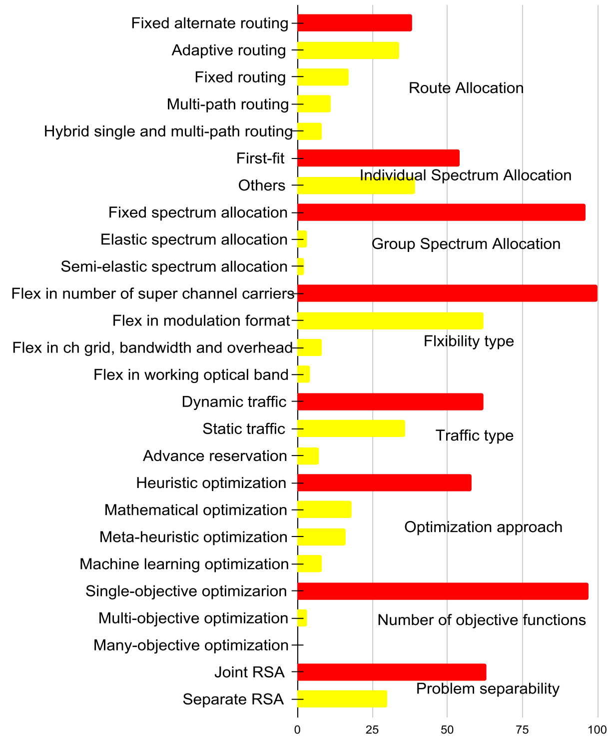


FIGURE 5. Histogram based on Table 2, with classification sub-criteria on the y-axis and percentage of occurrence on the x-axis.

the studied occurrences. Most authors have solved the optimization problem in EON as a single-objective problem because it is possible to convert multi-objective problems into single-objective problems using techniques such as weighted sum, as stated in [69].

In the case of problem separability, the Joint RSA is the most used compared to the separate RSA, given that with 63% and 30% of studied occurrences, respectively, the solutions obtained with Joint RSA are closer to optimal values than those obtained with separate RSA [1], [25].

Figure 5 shows a histogram based on Table 2; the sub-criteria of each criterion are grouped from highest to lowest, with red bars indicating the sub-criteria with the highest occurrence. We can see that the most used strategies for each classification criterion are fixed alternate routing, first-fit spectrum allocation, fixed spectrum allocation, flexibility in several super-channel carriers, dynamic traffic, heuristic optimization, single-objective optimization, and join RSA.

Considering the taxonomy in Tables 3 and 4, the cell colors indicate the number of algorithms found for each case, as explained in Section IX, because we observed many blank cells, indicating many possible research topics to be explored. We focused on cases with the largest occurrence, but, which occupied fewer cells in the table (marked in yellow and red).

From highest to lowest occurrence, we first have the cells marked in red, which represent the following combinations:

1) fixed spectrum allocation, flexibility in number of carrier super-channels, dynamic traffic, heuristic, single-objective optimization, and joint RSA;

2) fixed spectrum allocation, flexibility in number of carrier super-channels, dynamic traffic, heuristic, single-objective optimization and separate RSA.

For cells with a yellow background, we grouped combinations with the same number of occurrences in the same item and found the following types:

1) First-fit spectrum allocation, flexibility in number of carrier super-channels, dynamic traffic, heuristic, single-objective optimization, and joint RSA.
2) Fixed spectrum allocation, flexibility in modulation format, dynamic traffic, heuristic, single-objective optimization, joint RSA
3) Adaptive routing, flexibility in number of carrier super-channels, dynamic traffic, heuristic, single-objective optimization, join RSA
4) Fixed alternate routing, flexibility in number of carrier super-channels, dynamic traffic, heuristic, single-objective optimization, separate RSA. Other types of individual request spectrum allocation, flexibility in number of carrier super-channels, dynamic traffic, heuristic, single-objective optimization, separate RSA
5) First-fit, flexibility in modulation format, dynamic traffic, heuristic, single-objective optimization, joint RSA; Fixed spectrum allocation, flexibility in number of carrier super-channels, static traffic, mathematical optimization, single-objective optimization, joint RSA.
6) Fixed spectrum allocation, flexibility in modulation format, dynamic traffic, heuristic, single-objective optimization, separate RSA.

The two groups of combinations presented above are the most studied in the area, given the number of occurrences when studying the 120 algorithms found in specialized literature.

B. RESEARCH OPPORTUNITIES

This section presents the topics with the fewest entries in Tables 3 and 4, representing possible research opportunities given their poor treatment in the literature.

The following topics are little addressed in the literature because they may have more disadvantages than advantages. With the information available in the papers reviewed so far, we can neither affirm nor deny that this or that approach should be discarded or considered, but we can affirm that further study is needed to discard or consider the following approaches.

The *multi-path* [5], [26], [37], [116], [124], [125], [126], and *hybrid single multi-path* [5], [32], [36], [37], [99], [114] strategies have a similar and reduced percentage of use, both with 11% and 8% of studied occurrences, respectively, which indicates that much research can still be done using these strategies.

In *spectrum allocation to group connections*, *semi-elastic* and *elastic* alternatives had similar percentage uses, with 2% and 3% of the studied occurrences, respectively, which were lower than that of the *fixed* alternative. This may be because *semi-elastic* and *elastic* strategies require a network that uses specialized hardware to handle such an approach, as indicated by [93]. However, technological advances have reduced the costs of complex networks; therefore, these strategies are research options [46], [93], [94].

Flexibility in working optical band and *flexibility in channel grid, bandwidth, and overhead* have been studied, both with only 4% [5], [57], [117] and 8% [27], [37], [49], [108], [111] of studied occurrences, respectively. In both cases, specialized hardware is required, as explained in [12] and [5].

In the case of *flexibility in channel grid, bandwidth and overhead*, the exploration is recent, according to [37] and [49].

The authors of [62] and [99] stated that advance reservation (7% of studied occurrences) [31], [98], [99], [100], [101], [102], [114] is a novel approach in EON; therefore, it is a candidate area to be explored in future research.

The slight use of *meta-heuristics* (16% of the studied occurrences) [27], [28], [30], [50], [94], [97], [103], [104], [105], [110], [112], [113], [124], [126] indicates that this is a possible research opportunity for future improvements.

Machine learning techniques (8% of the studied occurrences) classify the relevant parameters of network operations [107], [119]. The most efficient routing and spectrum allocation option was selected using machine learning techniques. Network management and control must be changed to accommodate machine learning capabilities [29], [118]. Zhu et al. [31] used deep reinforcement learning (DRL) to solve the advance reservation (AR) problem within the RMSA in an EON. Chen et al. [120] and Koch et al. [121] used ML to optimize the resource allocation. Chen et al. [122] and Tang et al. [123] studied methods to reduce the training time of optimizers using ML.

There are only 3% of occurrences for *multi-objective optimization*; [30], [103], [126] use techniques based on genetic algorithms, whereas [34] use machine learning to deal with multi-objective optimization. There are 0% occurrences for *many-objective optimization*. There is a huge research opportunity in the cases of multi-objective and many-objective optimization, considering that according to [103], the optimization problems in EON are mainly of more than one objective.

According to [10], *separate* $R + SA$ has the advantage of lower computational cost than *joint RSA* and could be a good research opportunity. From a more detailed observation of Tables 3 and 4, we note that there are no studies based on *multi-objective optimization* and *mathematical optimization*. Furthermore, we did not find studies that solved multi-objective optimization using ILP or MILP.

If it is possible to solve a multi-objective problem using the indicated methods, this may be a good opportunity for future research.

We also noted that we did not find studies that performed *multi-objective optimization* for cases of *fixed*, *adaptive*, and *single- or multi-path hybrid* routing schemes. There

TABLE 3. Taxonomy of the studied RSA algorithms (Part 1).

			VI-A				VI-B				VI-C				VI-D			
			VII-A		VII-B		VII-A		VII-B		VII-A		VII-B		VII-A		VII-B	
			VIII-A	VIII-B	VIII-A	VIII-B	VIII-A	VIII-B	VIII-A	VIII-B	VIII-A	VIII-B	VIII-A	VIII-B	VIII-A	VIII-B	VIII-A	VIII-B
III-A1a	IV-A	V-A																
		V-B																
		V-C																
	IV-B	V-A					[71] [127]								[29]			
		V-B	[21] [96] [97] [97]								[97]							
		V-C																
	IV-C	V-A					[71] [127]	[40] [45] [41] [41]							[29]			
		V-B	[92], [94], [94], [95] [21] [96] [97] [97]	[94] [94]			[93] [93] [93]				[97]							
		V-C																
	IV-D	V-A																
		V-B																
		V-C																
III-A1b	IV-A	V-A						[49]										
		V-B	[37]															
		V-C																
	IV-B	V-A	[127]				[16], [18], [35], [99] [36] [38] [32]	[98] [86] [22] [22] [127] [106] [49]							[107]			
		V-B	[104] [37] [33]	[25] [26]			[21] [18] [96] [96]				[104] [104] [50]							
		V-C					[99] [100] [102] [102]	[98] [101]										
	IV-C	V-A	[127]				[99] [35] [18] [16] [36] [5] [38] [32]	[85], [85], [85], [98] [83] [22], [74], [86] [20], [22] [49], [106], [127]			[105] [105]	[28]			[31] [107]			[34]
		V-B	[104] [37] [39] [33]	[25] [26]			[21] [18] [96] [96]	[95]			[104] [104] [50]		[30] [103]		[31]			
		V-C					[99] [100] [102] [102]	[98] [101]							[31]			
	IV-D	V-A					[5]											
		V-B																
		V-C																
III-A1c	IV-A	V-A					[37], [37], [108] [37] [111]											
		V-B									[27] [27]							
		V-C																
	IV-B	V-A					[108] [78] [80] [86] [36] [37] [37] [37] [76] [114] [115] [116]	[75] [81]			[113] [113] [113]				[118] [119] [120] [121] [122]	[119] [123]		
		V-B		[26]			[77]				[27] [27]							
		V-C					[114]											
	IV-C	V-A					[108] [78] [79] [109] [72] [80] [86] [61] [82] [82] [36] [37] [37] [37] [111] [76] [114] [115] [84] [116]	[75] [81] [73] [117]			[112] [113] [113] [113]	[110]			[118] [119] [120] [121] [122]	[119] [123]		
		V-B		[26]			[77]	[57]			[27] [27]	[94]						
		V-C					[114]											
	IV-D	V-A						[117]										
		V-B						[57]										
		V-C																
III-A2	IV-A	V-A					[37] [37] [37]											
		V-B																
		V-C																
	IV-B	V-A					[37] [37] [37] [116]							[126]				
		V-B	[124]	[26] [26] [26]				[124]				[124]						
		V-C																
	IV-C	V-A					[125] [5] [37] [37] [37] [116]							[126]				
		V-B	[124]	[26] [26] [26]				[124]				[124]						
		V-C																
	IV-D	V-A					[5]											
		V-B																
		V-C																
III-A3	IV-A	V-A					[37] [37] [37]											
		V-B																
		V-C																
	IV-B	V-A					[99] [36] [36] [37] [37] [37] [32] [114]											
		V-B																
		V-C					[99] [114]											
	IV-C	V-A					[99] [36] [36] [5] [37] [37] [37] [32] [114]											
		V-B																
		V-C					[99] [114]											
	IV-D	V-A					[5]											
		V-B																
		V-C																

TABLE 4. Taxonomy of the studied RSA algorithms (Part 2).

			VI-A				VI-B				VI-C				VI-D			
			VII-A		VII-B		VII-A		VII-B		VII-A		VII-B		VII-A		VII-B	
			VIII-A	VIII-B	VIII-A	VIII-B	VIII-A	VIII-B	VIII-A	VIII-B	VIII-A	VIII-B	VIII-A	VIII-B	VIII-A	VIII-B	VIII-A	VIII-B
III-B1a	IV-A	V-A					[37] [37] [37] [111]											
		V-B	[37]								[27] [27]							
		V-C																
	IV-B	V-A					[80] [18] [16] [71] [36] [36] [37] [37] [37] [38] [115]	[98] [81] [22]			[113] [113] [113]			[126]	[107] [118] [120] [122]	[123]		
		V-B	[21] [96] [104] [37]				[21] [18] [96] [96]				[104] [104] [50] [27] [27]							
		V-C					[102]	[98]										
	IV-C	V-A					[109] [72] [80] [18] [16] [71] [82] [82] [36] [36] [125] [5] [5] [5] [37] [37] [37] [111] [38] [115] [84]	[85] [85] [85] [98] [74] [81] [22] [73]			[105] [105] [113] [113] [113]	[28]		[126]	[107] [118] [120] [122]	[123]		
		V-B	[94] [94] [95] [21] [96] [104] [37] [39]	[94] [94]			[21] [18] [96] [96]	[95] [57]			[104] [104] [50] [27] [27]	[94]	[103]					
		V-C					[102]	[98]										
	IV-D	V-A					[5] [5] [5]											
		V-B						[57]										
		V-C																
III-B1b	IV-A	V-A					[108]	[49]										
		V-B																
		V-C																
	IV-B	V-A	[127]				[108] [99] [78] [35] [86] [127] [32] [76] [114] [116]	[75] [86] [22] [127] [106] [49]							[29] [119] [121]	[119]		
		V-B	[97] [97] [124] [33]	[25] [26] [26] [26] [26] [26]			[77]	[124]			[97]	[124]						
		V-C					[99] [100] [102] [114]	[101]										
	IV-C	V-A	[127]				[108] [99] [78] [79] [35] [86] [61] [127] [32] [76] [114] [116]	[83] [74] [75] [86] [22] [20] [40] [45] [127] [106] [41] [41] [49] [117]			[112]	[110]			[31] [29] [119] [121]	[119]		[34]
		V-B	[92] [97] [97] [124] [33]	[25] [26] [26] [26] [26] [26]			[93] [93] [93] [77]	[124]			[97]	[124]	[30]		[31]			
		V-C					[99] [100] [102] [114]	[101]							[31]			
	IV-D	V-A						[117]										
		V-B																
		V-C																
III-B2a	IV-A	V-A					[108] [37] [37] [37] [111]	[49]										
		V-B	[37]								[27] [27]							
		V-C																
	IV-B	V-A	[127]				[108] [99] [78] [35] [80] [86] [18] [16] [71] [127] [36] [36] [37] [37] [37] [38] [32] [76] [114] [115] [116]	[98] [75] [81] [86] [22] [22] [127] [106] [49]			[113] [113] [113]			[126]	[107] [29] [118] [119] [120] [121] [122]	[119] [123]		
		V-B	[21] [96] [97] [97] [124] [104] [37] [33]	[25] [26] [26] [26] [26] [26]			[21] [18] [96] [96] [77]	[124]			[97] [104] [104] [50] [27] [27]	[124]						
		V-C					[99] [100] [102] [102] [114]	[98] [101]										
	IV-C	V-A	[127]				[108] [99] [78] [79] [35] [109] [72] [80] [86] [18] [16] [61] [71] [127] [82] [82] [36] [36] [125] [5] [5] [5] [37] [37] [37] [111] [38] [32] [76] [114] [115] [84] [116]	[85] [85] [85] [98] [83] [74] [75] [81] [86] [22] [22] [20] [73] [40] [45] [127] [106] [41] [41] [49] [117]			[105] [105] [112] [113] [113] [113]	[28] [110]		[126]	[31] [107] [29] [118] [119] [120] [121] [122]	[119] [123]		[34]
		V-B	[92] [95] [21] [96] [97] [97] [124] [104] [37] [39] [33]	[94] [25] [26] [26] [26] [26] [26]			[93] [21] [18] [96] [96] [77]	[95] [124] [57]			[97] [104] [104] [50] [27] [27]	[94] [124]	[30] [103]		[31]			
		V-C					[99] [100] [102] [102] [114]	[98] [101]							[31]			
	IV-D	V-A					[5] [5] [5]	[117]										
		V-B						[57]										
		V-C																
III-B2b	IV-A	V-A																
		V-B																
		V-C																
	IV-B	V-A																
		V-B																
		V-C																
	IV-C	V-A																
		V-B	[94]				[93]											
		V-C																
	IV-D	V-A																
		V-B																
		V-C																
III-B2c	IV-A	V-A																
		V-B																
		V-C																
	IV-B	V-A																
		V-B																
		V-C																
	IV-C	V-A																
		V-B	[94]	[94]			[93]											
		V-C																
	IV-D	V-A																
		V-B																
		V-C																

are no technical limitations to studying *multi-objective optimization* in cases of *fixed*, *adaptive*, and *single- or multi-path hybrid* routing schemes; therefore, it is a good research opportunity. We also did not find studies that used *single- or multi-path hybrid routing schemes* along with *mathematical optimization* or *meta-heuristics*, whereas within the *heuristics*, we did not find studies that solved the problem with a *separate approach*.

Finally, we did not find any papers dealing with the solution of the RSA problem using *semi-elastic* and *elastic spectrum allocation* together with *multi-objective optimization* or *meta-heuristics*, nor did we observe the use of the separate solution approach in this context.

XI. CONCLUSION

In this study, a novel taxonomy system for RSA algorithms in EONs is presented, which can be used as follows: (1) providing a classification of published work and (2) facilitating the visualization of future research opportunities.

To the best of our knowledge, this is the first study to investigate RSA algorithms in EONs that present a complete taxonomy model, along with its associated classification criteria.

The following combination of strategies is the most widely used in the literature and, therefore, the most mature in the field: fixed alternate routing, first-fit spectrum allocation, fixed spectrum allocation, flexibility in number of super-channel carriers, dynamic traffic, heuristic optimization, single-objective optimization and join RSA.

We envisage the following strategies to be explored in the future as standalone and in combination to holistically realize the potential of EON:

- hybrid single and multi-path route allocation,
- multi-path route allocation,
- elastic and semi-elastic spectrum allocation approaches,
- channel grid, bandwidth and overhead flexibility type,
- advance reservation type of traffic,
- meta-heuristic optimization approach,
- machine learning as optimization approach,
- multi and many-objective optimizations.

In future work, the authors propose to develop a taxonomy that considers spatial division multiplexing and impairment issues.

ACKNOWLEDGMENT

The authors would like to thank the anonymous reviewers whose comments have contributed to the improvement of the quality of this work.

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