PHYSICAL LAYER-AWARE CIRCUIT REALLOCATION TO EONS USING MAKE-BEFORE-BREAK AND PUSH-PULL TECHNIQUES

Selles Araújo[1,2], Jurandir Lacerda Jr.[1], Alexandre Fontinele[2], Érico Leão[2],
José Valdemir d. Reis Jr.[2], André Soares[2]
[1]Instituto Federal do Piauí, Teresina-PI, Brazil, [2]Universidade Federal do Piauí, Teresina-PI, Brazil

NOTE: Corresponding author: Selles Araújo, sellesgustavo@gmail.com

Abstract – *This paper proposes a new circuit reallocation algorithm with make-before-break and push-pull techniques that considers the effects of physical layers in transparent elastic optical networks called Just One Circuit Reallocation (JOC). The JOC algorithm reallocates just one already established circuit to avoid blocking new circuit requests due to impairments in the physical layer. The results of the JOC algorithm were compared to three other algorithms: Circuit Reallocation Strategy - Physical Layer (CRS-PL), Circuit Reallocation for Block Reduction related to the QoT of the circuits (R-RQoT), and Make-Before-Break based defragmentation algorithm (MBBr). The reallocation algorithms are evaluated under the Bandwidth Blocking Probability (BBP), Circuit Blocking Probability (CBP), and the Number of reallocated circuits (N), external fragmentation, and percerntual of circuit by modulation for USA and EON topologies. Moreover, we also evaluated the performance of reallocation algorithms using complete sharing, K-shortest path computation, modified Dijkstra paths computation, and K-shortest path with reduction of QoTO to routing and spectrum assignment. Simulation results show that the proposed algorithm performs better than the CRS-PL, R-RQoT, and MBBr algorithms regarding BBP, PBC, and N. Regarding BBP, our algorithm presented minimum reductions of approximately 65.36% e 55.6% for the USA and EON topology, respectively.*

Keywords – Circuit reallocation, elastic optical network, make-before-break, OFDM, push-pull

1. INTRODUCTION

Data traffic on the Internet is growing significantly, and the promising network infrastructure to handle this growth is Elastic Optical Networks (EONs). The advantage of EONs consists of using resources more efficiently compared to traditional networks. Efficiency is achieved by fairer allocation of the optical spectrum due to the frequency channels having a size of 6GHz or 12GHz, a size sufficiently adequate for resource waste to be reduced from the 50GHz size of traditional networks [1].

Frequency channels are called slots and can be combined to meet traffic requests that require greater bandwidth. This division of resources into small frequency intervals is due to using the Orthogonal Frequency Division Multiplexing (OFDM) technique by EONs [1, 2].

In EONs, a circuit request arrives on the network, and establishing it requires a solution to the Routing, Modulation Level, and Spectrum Assignment (RMLSA) problem [2]. This problem involves choosing the route, modulation, and spectrum band for a given request. All requests are submitted to the RMLSA problem, and when any of the sub-problems are not solved, the request is blocked.

Choosing the spectrum band consists of selecting a set of slots that are contiguous and continuous. Continuity and contiguity are restrictions of the optical medium that need to be met due to EONs being transparent [2]; that is, there is no conversion of the optical signal in intermediate nodes between the origin and destination of the request. The spectrum contiguity constraint requires that the slots be adjacent. Continuity requires the slots to be the same on all links on the defined route. Contiguity and continuity are optical constraints that must be met to establish the circuit [2]. Meeting these restrictions becomes difficult when the spectrum is fragmented.

Fragmentation is a common EONs problem that contributes to request blocking. This problem occurs due to the successive establishment and termination of circuits in a network scenario with dynamic traffic [2]. The consequence of the problem is that small blocks of free slots are distributed across the spectrum, contributing to the non-contiguity and continuity of the spectrum. A solution widely used in the literature is the adoption of spectrum defragmentation algorithms.

Defragmentation algorithms reallocate active circuits to reorganize spectrum use, aiming to generate blocks of contiguous and continuous free slots in the network. Reallocation seeks to find a new route or set of slots for an active circuit, changing the initial RMLSA solution. This strategic change significantly reduces request blocking on the network [3, 4].

Defragmentation is interesting in network scenarios where fragmentation is the main cause of blockages, and these are generally scenarios that do not take Physical Layer Imperfections (PLIs) into account. In scenarios where PLIs are considered, the main causes of request blocking are related to the inadequate transmission quality (QoT) that circuits present when subjected to the effects of the physical layer [5].

In this sense, circuit reallocations used to defragment are now used to reduce physical layer effects on the network.

These reallocations reorganize active circuits, changing their routes and, consequently, reducing interference in regions of the network that are suffering greatly from the effects. If reallocations are not made in these regions (links), the admission of requests in these areas is compromised [6].

In the article proposed in [7], a circuit reallocation algorithm was presented to reduce physical layer blockages. The execution of the algorithm starts when a request is about to be blocked, and for each reallocation process, a single circuit is identified and reallocated, capable of reducing the physical layer effects on the request route enough so that the request does not suffer the block. This work is an extension of [7]'s proposal, with the difference of using the push-pull technique to compress the spectrum in situations of circuit completion and reallocation of the circuit through the proposal.

The organization of this work consists of the following: Section 2 describes the adopted physical layer model and explains the physical layer effects used. Section 3 presents the problem of reallocating circuits to reduce physical layer effects and, consequently, QoT-related blockages. Section 4 lists the work related to the reallocation problem, where most reallocate to defragment. In Section 5, the operation of the reallocation algorithm is presented, and in Section 6, the performance evaluation shows the impact of using the proposal in different simulation scenarios. Finally, conclusions are presented in Section 7.

2. PHYSICAL LAYER MODEL

In the literature, physical layer effects can be categorized into linear effects, nonlinear effects and other effects [8]. Linear effects are independent of the optical signal power and affect each circuit separately [9]. Examples of this type of effect are fiber attenuation, chromatic dispersion and polarization mode dispersion.

The nonlinear effects are strongly dependent on the accumulated power and the individual power of the optical circuits transported in parallel in the same fiber, causing interference in the individual circuits and between them [9]. Self-phase modulation, cross-phase modulation and four-wave mixing are examples of nonlinear effects.

The effects of the third category are related to the optical devices present in the network or the current state of circuit allocation [8]. The main effects of this category are crosstalk, resulting from the incomplete isolation of the circuits by optical components, and Amplified Spontaneous Emission (ASE), noise generated at the time of amplification of the optical signal by the Erbium Doped Fiber Amplifer (EDFA).

ASE effects and nonlinear effects were adopted in this work because they are in line with what the literature adopts [10]. The physical layer model used was proposed by [11] and the Signal to Noise Ratio (SNR) was used to measure the QoT of the optical circuits. The SNR calculation of a circuit c is defined by Equation *(1)*: [11].

$$SNR_c = \frac{I}{I_{ASE} + I_{NLI}}. \tag{1}$$

The parameter I corresponds to the signal Power Spectral Density (PSD), defined by $I = P_{tx}/\Delta_f$, where P_{tx} is the power signal and Δ_f is the circuit bandwidth. The PSD of ASE noise (I_{ASE}) and nonlinear noises (I_{NLI}) are demonstrated in detail in [5].

The SNR level is calculated for each circuit to be established in the network and its value must be greater than or equal to the modulation format threshold selected by the RMLSA algorithm. If the SNR is not adequate, the request may be blocked by QoT on the New circuit (QoTN) or QoT on Other already established circuits(QoTO). QoTN is the blocking suffered when the SNR of the new request does not present adequate levels for its operation. QoTO occurs when even if a new request has adequate QoT, its establishment impacts already active circuits, leaving them with QoT below the threshold required by the network.

3. CIRCUIT REALLOCATION

Circuit reallocation appeared in EONs to defragment the optical spectrum, a process similar to defragmenting a hard drive. Defragmentation generates free space on the disk capable of admitting more files, just as optical networks can admit more traffic when using this procedure. The work proposed by [12] was one of the precursors of defragmentation for optical networks.

The circuit reallocation process consists of searching for a new RMLSA solution for a given active circuit in the network. Using the new solution, the circuit may be reallocated to a new route, or the route may not be changed, just changing the spectrum band of the circuit. With this approach, algorithms can be categorized into re-routing algorithms or spectral reassignment algorithms. Algorithms that change circuit routes have more possibilities for reallocation and, therefore, can have a greater positive impact on the network [2].

The new solution for reallocating the defined circuit seeks to migrate data traffic using techniques that redirect connection traffic. Migration can occur by interrupting circuit services, causing data loss, or by not interrupting services, a process that does not result in data loss. There are several techniques in the literature for traffic migration; they are: i) re-optimization, ii) hop-tuning, iii) push-pull, and iv) make-before-break [2].

Therefore, the reoptimization technique causes traffic interruption and is known in the literature as a non-hitless technique. On the contrary, the other techniques that, when used, do not interrupt traffic are called hitless techniques. Generally, jobs are categorized according to rerouting criteria and data migration technique [2].

What sets the work apart is the strategy adopted to define which circuits should be reallocated and what is the new RMLSA solution for each circuit. To defragment the spectrum, the new solution seeks to meet this requirement and generate blocks of contiguous and continuous slots

in parts of the network. However, when physical layer imperfections are considered in the study, the fragmentation problem is no longer significant [13].
In these physical layer scenarios, interference from circuits to each other and from these circuits to future requests are the main factors in request blocking, as seen in the work proposed by [13, 6, 7]. In this sense, circuit reallocations now have another objective: to reduce the physical layer effects considered so that interferences are mitigated. This contributes significantly to improvements in the QoT of new requests.
In this context, the problem of Circuit Reallocation aware of Physical Layer Imperfections (CR-PLI) arises, in which reallocations are made to reduce the effects of noise produced by network equipment or the leakage of circuit powers. However, CR-PLI is a problem similar to spectrum defragmentation with a different objective. The same steps followed by defragmentation are also adopted in CR-PLI, which can be divided into:

1. **Step 1**: When to run the reallocation algorithm? (Trigger)
2. **Step 2**: Which circuits will be reallocated?
3. **Step 3**: What is the new RMLSA solution for each circuit to be reallocated?
4. **Step 4**: Which technique should be used to migrate data traffic from circuits?

A CR-PLI algorithm needs to solve each step listed to operate in the network, and different ways of dealing with the steps generate different results in network performance. It is worth mentioning that fragmentation can also be reduced depending on the heuristic adopted to solve the CR-PLI problem. Fig. 1 presents an example of the CR-PLI problem.

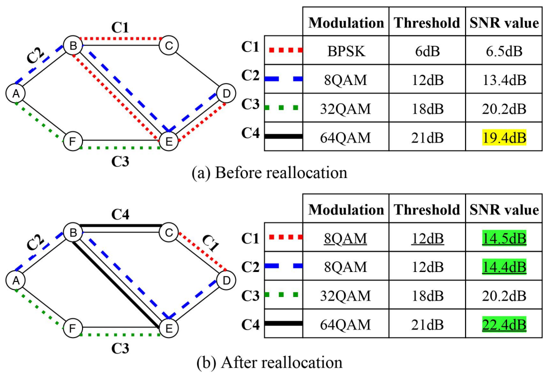

Figure 1 – Example of the CR-PLI problem. Network scenario (a) before and (b) after circuit reallocation to reduce physical layer effects.

In the scenario in Fig. 1(a), the new circuit request (Circuit 4) would be blocked when allocated to route C-B-E. The blocking occurs due to the high interference generated by the circuits that share the B-E link in the new request. This interference is high enough to make the QoT of circuit 4 inadequate, with an SNR equal to 19.4 dB, lower than the modulation threshold considered (21 dB). This leads to QoTN blocking.
In the scenario in Fig. 1(b), circuit 1 was reallocated from route C-B-E-D to route C-D. This reallocation caused a reduction in physical layer effects on the C-B-E-D route links and, therefore, it was possible to allocate circuit 4 (new request) in the network with adequate SNR levels (previously 19.4 dB, now 22.4 dB).

4. RELATED WORKS

The vast majority of work in the literature on elastic optical networks involves circuit reallocation, seeking to defragment the spectrum to reduce fragmentation and enable greater admission of traffic into the network [12, 4, 14, 15, 16, 17]. However, the trick of reallocating circuits can be used to achieve other objectives, such as reducing physical layer effects.
The authors in [12] present a hitless defragmentation algorithm that allows circuits to be rerouted, changing their original RMLSA solution. The circuits chosen for reallocation interfere with the new request and contribute to its possible blocking. These circuits are reallocated to different routes to establish the new request. The technique used to migrate data traffic is make-before-break, also proposed by the same author [12] and widely used in the literature.
The authors in [3] present the defragmentation problem and propose a solution. The proposed algorithm uses the Most Frequently Used Slot First (MFUSF) and Highest Used Slot-Index First (HUSIF) strategy to select the 30% of active circuits for reallocation. RMLSA algorithms define the new RMLSA solution for circuits in the network, and data traffic migrations are performed using the make-before-break technique.
The disadvantage of the make-before-break technique is the need to use additional transmitters and receivers. To deal with this, new traffic migration techniques, such as push-pull [18] and hop-tuning [19], were proposed, and consequently, new defragmentation work went to use them. In [19], in addition to proposing the hop-tuning technique, an experiment is carried out detailing its operation and presenting its benefits.
Another form of reallocation, generally known as truly-hitless, uses survivable scenarios and does not require traffic migration techniques [14, 15]. In [15], dedicated protection is used to reallocate both primary and secondary circuits without interrupting network services. The non-interruption is due to the possibility of the primary circuits exchanging functions with the secondary circuits to be reallocated and vice versa. Thus, if a secondary circuit is chosen for reallocation, it is deactivated from the network and re-established in a new RMLSA solution. The connection will not be impaired as data continues transmitting via the primary path. Similar proposals are found in [20].
In [21], two metaheuristics are presented to select active circuits in the defragmentation process. The first is based

on ant colonies, and the second is based on a genetic algorithm. The goal is to reduce the number of circuits reallocated and reduce fragmentation in the network. In another work by the same author ([17]), a method for estimating the request blocking rate based on machine learning is proposed. This method is used as a trigger for the defragmentation process. The proposal is compared with other triggers, one with a fixed time and the other evaluating fragmentation in the network. The machine learning-based trigger showed a lower probability of blocking using the same reallocation strategies with only a change in the trigger.

Unlike defragmentation work, the proposals presented by [13, 6] seek to reallocate circuits to reduce the effects generated by considering the physical layer. In [13], the reallocation algorithm is executed for each blockage caused by a lack of transmission quality to minimize interference on the links on the blocking route. In addition to minimizing physical layer effects, circuit rerouting seeks to balance network load, a contributing factor to reducing interference on network links. In [6], the reorganization of the circuits aims for a local benefit, focusing on establishing the Requisition on the Imminence of Blocking (RIB). The proposal's difference is the restriction on reallocating only one circuit per process, reducing the number of changes in the network.

The authors in [16] also consider physical layer imperfections, proposing a proactive defragmentation scheme aware of optical signal quality. The scheme seeks to minimize spectrum fragmentation and maintain the circuit's transmission quality using two algorithms: awareness of nonlinear effects and ignorance of linear effects. Additionally, machine learning is used to estimate the transmission quality of the circuit during reallocation. The experiments showed that the nonlinear effect-aware algorithm reduced the blocking rate by more than 24% compared to the effect-unaware algorithm, considering the USA topology.

Unlike the works above, this work uses the circuit reallocation approach to directly reduce physical layer effects in favor of meeting imminent blocking requests. For each execution of the algorithm, at most, a single circuit is reallocated, and the reallocation is only carried out on the physical network if it is possible to avoid blocking the imminent blocking request. This work is an extension of the [7] work, with the addition of more performance metrics and the use of the push-pull technique to increase the possibilities of reallocation in the network since the use of the make-before-break technique adds an extra cost in the network, that is, more transmitters are necessary for its operation.

5. PROPOSAL

This section presents the physical layer-aware reallocation algorithm based on push-pull and make-before-break techniques, called Just One Circuit Reallocation per Process (JOC). Reallocations using make-before-break undergo route changes, and reallocations using push-pull do not undergo rerouting only spectrum reassignment. Generally, push-pull reallocations compress the spectrum into a route when a circuit is rerouted, and non-contiguous space is generated. Fig. 2 shows the flowchart of the normal operational functioning of the network with reallocations using push-pull when circuits are terminated.

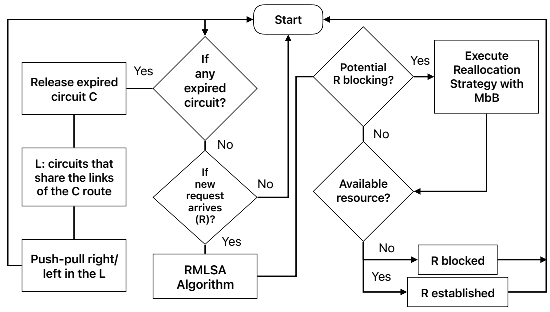

Figure 2 – Normal network operation with the adoption of the push-pull technique.

It is observed that when the circuit is terminated (C_f) in the network, a push-pull reallocation operation is performed to compress the spectrum along the C_f route when necessary. Generally, the completion of circuits contributes to disorganized spectrum use. The active circuits that will take part in the push-pull operation share the C_f route links and are ordered increasingly from the circuit closest to the beginning of the spectrum to the one closest to the end. Then, the circuits are moved using the push-pull technique to the beginning or end of the spectrum, depending on the spectrum allocation policy.

The other reallocation operation will be when the network detects a potential request blockage. Potential blocking means the request will be blocked if the network does not undergo any changes. From this, a reallocation strategy is executed, selecting the circuits that share the links of the R request route (potential blocking request) and choosing one to be rerouted, ensuring that request R is met. If rerouting a single circuit is impossible, nothing is done on the network, and the R request is blocked. The objective of reallocating a single circuit per process is to reduce the number of operations, complexity, and cost, as the make-before-break technique uses additional transmitters and receivers. Fig. 3 details how the reallocation strategy works.

In Fig. 3, the selected circuits are ordered by decreasing hop number, since the reallocation of larger circuits according to this criterion may produce more positive effects on the network but they are circuits that are more difficult to reroute. For each selected circuit, a new RMLSA solution (new route, new modulation, and new spectrum) will be defined. If the new solution meets the QoT requirements, the circuit is reallocated using the make-before-break technique, and an attempt is made to meet the new imminent blocking request R. If request R

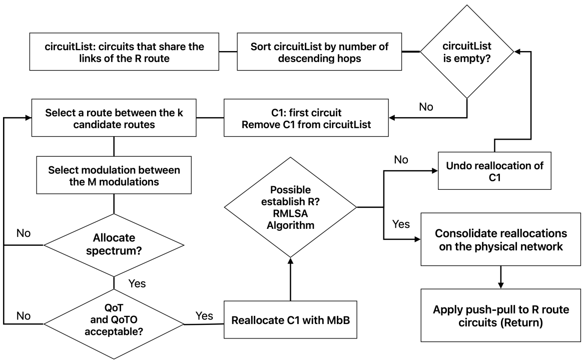

Figure 3 – Circuit reallocation strategy.

can be satisfied, the algorithm ends.

When a given circuit in the list of circuits does not meet all the requirements for reallocation, the next circuit in the list is searched, and the process is repeated. With each circuit rerouting, an attempt is made to satisfy the new request. Even with circuit reallocation, the new request cannot be met; the reallocation is undone, as the algorithm restricts it to a single reallocated circuit to avoid blocking. It is worth mentioning that this entire process is carried out in an auxiliary graph that reflects the physical network. The changes are reflected in the network when the algorithm's objective is successfully achieved.

Finally, with the reallocation of a single circuit to avoid blocking the R request, it will be assessed whether it is necessary to compress the spectrum where the circuit was disconnected. If so, the route circuits suffered spectrum slippage with the push-pull technique by the spectrum allocation policy of the RMLSA algorithm. An example is shown in Fig. 4.

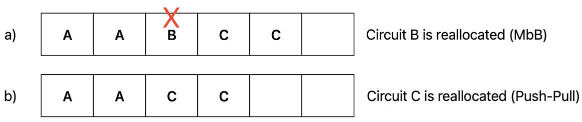

Figure 4 – Action of the push-pull technique.

Fig. 4 shows two spectrum scenarios with the rerouting of circuit B, which generated one available slot between circuits A and C. The circuit is slid and reallocated with the push-pull technique to compress the spectrum, strengthening the contiguity of free spectrum slots. This push-pull technique procedure is used in this case and when the circuits are completed, as shown in Fig. 2.

6. PERFORMANCE EVALUATION

To evaluate performance, computational simulations were carried out using the Slice Network Simulator (SNetS) simulation tool [22]. SNetS is a simulator of elastic optical networks, and based on implemented metrics, it is possible to perform a performance analysis comparing the proposal with its competitors in different network topologies. The USA and EON topologies were chosen for the experiments.

In each network topology, traffic loads were generated and measured in Erlangs, following the Poisson process and being uniformly distributed among all pairs of source and destination nodes in the network. The load adjustment was made not to exceed a 10% probability of circuit blockage. Traffic generation generates 100 000 circuit requests with bandwidths of 10, 40, 80, 100, 160, 200 and 400Gbps. The average retention time of the circuits follows a negative exponential distribution. Each simulation was replicated 10 times with different random variable generation seeds. For all results, the confidence level was 95%.

Four simulation scenarios were considered for each network topology. The difference between each scenario is the allocation algorithm. The reallocation algorithms are applied in each scenario to analyze the impact of reallocation in different scenarios since reallocating a circuit may be more difficult depending on the allocation algorithm. The following scenarios are: i) Complete Sharing (CS); ii) K-Shortest Path Computation (KSPC); iii) Modified Dijkstra Paths Computation (MDPC) and iv) K-Shortest Path with Reduction of QoTO (KSPCQoTO).

For each scenario, the following reallocation algorithms were used: Make-Before-Break based defragmentation algorithm (MBBr) [12], PLI-Aware Reallocation Algorithm (CRS-PLI) [6] and Reallocation Algorithm for Block Reduction by QoT (R-RQoT)[13]. Therefore, the MBBr algorithm is not PLI aware and unsuitable for dealing with the CR-PLI problem. The algorithms listed were compared to the proposal in this article, called JOC, proposed in [7] with some adaptations.

6.1 Bandwidth blocking probability

The following figures show the Bandwidth Blocking Probability (BBP) in the four above-mentioned scenarios. More details about this metric can be found in [23].

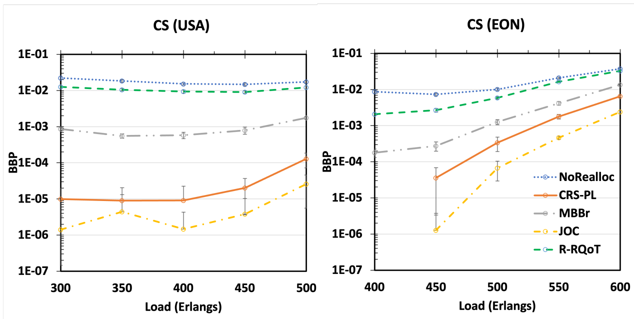

Figure 5 – BBP of reallocation algorithms (CS)

Fig. 5 presents the BBP of the reallocation algorithms in the CS allocation algorithm scenario for different topologies. It is observed that the JOC algorithm presented better performance in both topologies at all load points. At the last load point in both topologies, where the network is most stressed, the JOC algorithm achieved a significant block reduction, achieving more than 60% reduction compared to CRS-PL, the algorithm with the second best

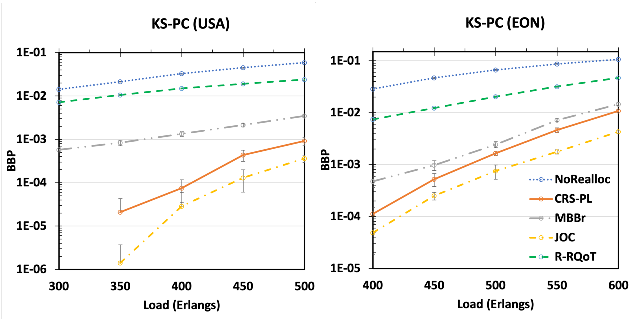

Figure 6 – BBP of reallocation algorithms (KS-PC).

In Fig. 6, the proposed algorithm performs better than competitors at all load points evaluated. The JOC algorithm achieved significant gains from the other algorithms for the USA topology and reduced BBP by over 90% compared to the no reallocation algorithm at the last load point. For this case, the EON topology's significant BBP reduction remains, achieving more than 60% BBP reduction compared to the CRS-PLI algorithm.

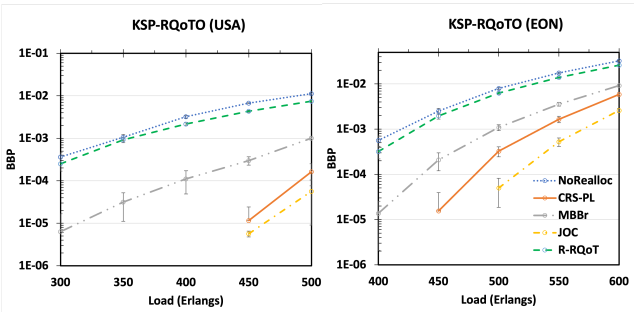

Figure 7 – BBP of reallocation algorithms (KSP-RQoTO).

For the scenario in Fig. 7, where the allocation algorithm is KSP-RQoTO, the allocation is the most optimized among all the scenarios evaluated. Consequently, reallocating a circuit becomes more difficult, as the circuits are already efficiently accommodated. Confirming the difficulty of reallocation is that this was the scenario in which the proposed algorithm obtained the lowest reduction in BBP compared to the other scenarios. The BBP reductions for the USA topology were around 55% and 65% for the EON topology, considering the last load point and compared to the CRS-PLI algorithm. Even though it was the smallest reduction, there were still significant reductions.

The scenario in Fig. 8 does not present any particular gains of the proposed algorithm for the others. BBP reductions were considerable, independent of topology. The minimum bandwidth blocking reduction for the scenario in Fig. 8 was at least 30% for both topologies.

6.2 Blocking components

The following tables present the percentage of blocking types for each allocation algorithm scenario (no reallocation), making a comparison with the proposed JOC algorithm. In all cases, QoTN and QoTO type blocks were the

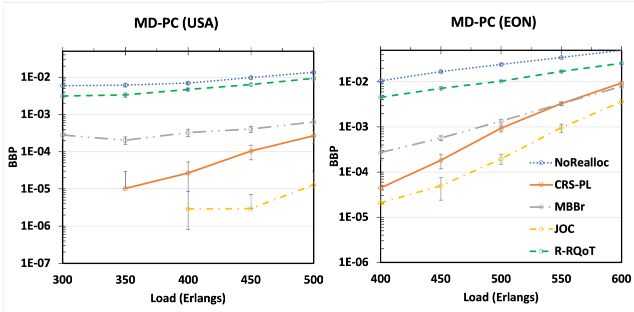

Figure 8 – BBP of reallocation algorithms (MD-PC).

most significant due to the consideration of the physical layer in the experiments. This shows that reallocations that mitigate physical layer blockages are more interesting than those that defragment the spectrum. In Tables 1, 2, 3 and 4, the percentages of blocking types for the USA topology are presented considering the latest load points on the network.

Table 1 – Blocking components in the CS scenario.

CS (No reallocation)				
Load	QoTN	QoTO	Frag	AFS
400	0.02%	1.16%	0.0001%	0,0001%
450	0.08%	1.01%	0.001%	0,0006%
500	**0.26**%	**0.88**%	0.005%	0,0016%
JOC				
400	0.0001%	0.0%	0.0%	0.0%
450	0.0002%	0.0001%	0.0%	0.000189%
500	**0.0009**%	**0.0001**%	0.0%	0.000189%

Table 1 shows the lock types of the CS (No reallocation) algorithm about the locks of the reallocation algorithm. It is observed that for the same load on the network, the reductions in the blocking percentage are considerable and that blocking per physical layer prevails. The blocking reductions were significant in the blocking types per physical layer due to the proposed reallocation algorithm having this objective. When loading 500 Erlangs, for example, QoTN blocking represented approximately 0.26% of the total blocking, and after using the JOC algorithm, blocking of this same type began to represent approximately 0.0009%. For QoTO type blocks, the reductions were similar.

Table 2 – Blocking components in the KS-PC scenario.

KS-PC (No reallocation)				
Load	QoTN	QoTO	Frag	AFS
400	1.09%	0.44%	0.04%	0,008%
450	1.66%	0.38%	0.07%	0,015%
500	**2.33**%	**0.39**%	0.11%	0,021%
JOC				
400	0.0008%	0.0001%	0.0%	0.0%
450	0.0050%	0.0005%	0.0%	0.0%
500	**0.0131**%	**0.0011**%	0.0001%	0.0%

Table 2 presents results similar to the scenario in the previous table. Applying the proposed reallocation strategy, physical layer locks prevail over other locks and suffer significant reductions. In all loads evaluated, the minimum gains were more than 80% for each type of physical layer blocking, which consequently avoided AFS type blocking and minimized Frag type blocking.

Table 3 – Blocking components in the KSP-RQoTO scenario.

KSP-RQoTO (No reallocation)				
Load	QoTN	QoTO	Frag	AFS
400	0.124%	0.0%	0.0086%	0,0029%
450	0.247%	0.0%	0.0221%	0,0047%
500	**0.441**%	0.0%	0.0362%	0,0084%
JOC				
400	0.0%	0.0%	0.0%	0.0%
450	0.0002%	0.0%	0.0%	0.0%
500	**0.0016**%	0.0%	0.0001%	0,0001%

For the scenario with the KSP-RQoTO allocation algorithm (Table 3), the types of physical layer locks were the ones that reduced the most with the JOC algorithm reallocations. However, the other types of blocking also achieved considerable reductions, showing 0.0% in loads 400 and 500 Erlangs. QoTO blocking was not computed because the KSP-RQoTO algorithm avoids this blocking as a strategy. Therefore, the JOC algorithm acted mainly on QoTO blocking, with the blocking percentage being reduced from 0.441% to 0.0016%.

Table 4 – Blocking components in the MD-PC scenario.

MD-PC (No reallocation)				
Load	QoTN	QoTO	Frag	AFS
400	0,121%	0,2794%	0,0071%	0,0016%
450	0,192%	0,3181%	0,0168%	0,0068%
500	**0,325**%	**0,3486**%	0,0346%	0,0223%
JOC				
400	0.0%	0.0%	0.0%	0.0%
450	0.00019%	0.0%	0.0%	0.0%
500	**0.00029**%	**0.0001**%	0.0%	0.0%

In Table 4, the behavior of significant reductions in physical layer type blocking (QoTN and QoTO) remains the same. The JOC reallocation algorithm, in this scenario, zeroed out Frag and AFS type blocks, in addition to drastically reducing QoTN and QoTO type blocks, which were the largest number of blocks. At all load points presented, the JOC algorithms caused block changes. In 500 Erlangs, for example, the blocking went from 0.325% to 0.00029% blocking, a reduction of more than 90%. The results for the EON topology had similar behavior.

6.3 Number of reallocated circuits

Figures 9 and 10 show the N [7] values of the reallocation strategies aware of physical layer imperfections for the topology USA. The values of N were obtained for the scenarios CS, KS-PC, KSP-RQoTO, and MD-PC, considering different traffic loads in the network.

Fig. 9(a) presents the N for the JOC, CRS-PL, and R-RQoT

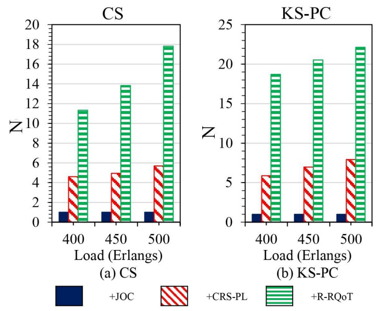

Figure 9 – N values for the USA topology in the scenarios (a) CS and (b) KS-PC.

strategies in the CS scenario. It is observed that the value of N of the JOC is the lowest among the strategies evaluated for all load points. In Fig. 9(b), the N values also remain the same for the JOC, corresponding to at most one reallocated circuit per reallocation process.

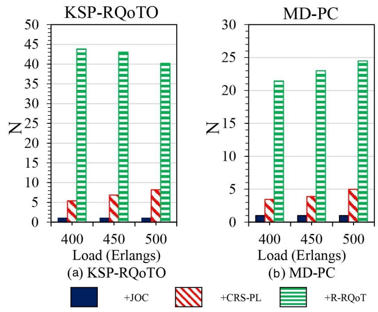

Figure 10 – N values for the USA topology in the scenarios (a) KSP-RQoTO and (b) MD-PC.

The N values of Fig. 10(a) are approximately 1, 8, and 40 for the JOC, CRS-PL, and R-RQoT strategies, respectively. Although in the KSP-RQoTO scenario, a reduction of N was observed for the CRS-PL algorithm, the JOC remains with only one process reallocated circuit. The same occurs for the scenario of Fig. 10(b), with the lowest value of the JOC algorithm.

The N metric was also evaluated in the different allocation algorithm scenarios for the EON topology. The numerical results of the N metric for the EON topology are presented in Fig. 11 and Fig. 12.

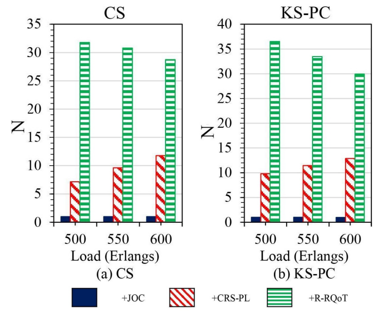

Figure 11 – N values for the EON topology in the scenarios (a) CS and (b) KS-PC.

Fig. 11(a) presents the values of N when the PLI-aware reallocation strategies are applied in the CS. For each traffic load studied, the value of N is approximately 1 for the +JOC algorithm. Similarly, in Fig. 11(b), the +JOC algorithm achieved the lowest N value when compared to other studied algorithms, with a mean of up to 1 process reallocated circuit for each traffic load. For example, under 450 erlangs, the +JOC algorithm reallocated just one circuit to avoid blocking requests, while the +CRS-PL algorithm required approximately 13 active circuits rerouting.

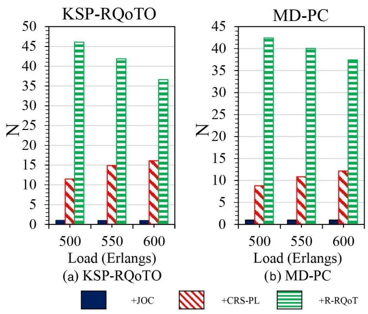

Figure 12 – N values for the EON topology in the scenarios (a) KSP-RQoTO and (b) MD-PC.

In Fig. 12(a), the results of the N were observed when the PLI strategies considered were applied to the KSP-RQoTO. The proposed algorithm presented the least number of circuits reallocated per process to the other strategies. Under 600 Erlangs, while the CRS-PL and R-RQoT algorithms achieved an approximate N value of 16 and 37, the +JOC has N equal to 1. As in Fig. 12(a), Fig. 12(b) also has an N value of 1, while +CRS-PL has N close to 37 considering the last loading point.

The N values of the JOC algorithm are equal to 1 under different traffic loads due to its heuristic that allows just one reallocation per process. The JOC heuristic minimizes network changes and dramatically decreases operational costs. Only the PLI-aware strategies were considered for analysis of the NCR_a values.

6.4 External fragmentation

The external fragmentation measure can be found in more detail in [2] and is used to measure the disorganization of the use of the optical spectrum. Figures 13, 14, 15 and 16 present external fragmentation in scenarios with different allocation algorithms in function of the load on the network.

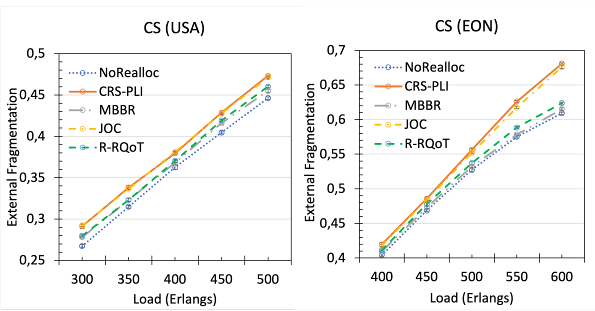

Figure 13 – External fragmentation (CS).

In Fig. 13, fragmentation in the USA topology does not show significant differences throughout the growth of the network load. However, it is observed that the reallocation algorithms aware of PLI, CRS-PLI, and JOC have higher fragmentation levels, especially because they do not focus on this problem. The JOC strategy of this work also seeks to mitigate the fragmentation carried out by push-pull at various moments in the simulations. In the EON topology, the highlight occurs in the last three load points, where the fragmentation levels showed a considerable difference. The R-RQoT algorithm and MBBr deal with the fragmentation problem in their strategies.

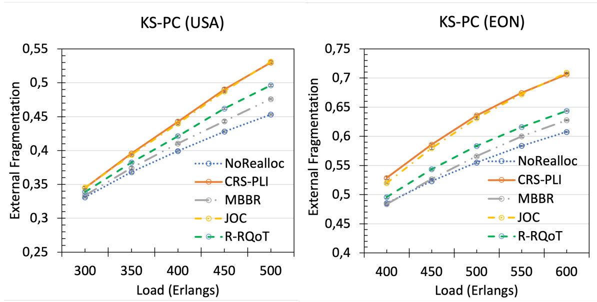

Figure 14 – External fragmentation (KS-PC).

Fig. 14 shows the external fragmentation for the KS-PC scenario. For both topologies, the algorithms that do not deal with fragmentation, CRS-PLI and JOC, performed worse than the others. The MBBr algorithm is a defragmentation algorithm and performed better than other reallocation algorithms due to its objective being defragmentation. While MBBr has about 62% fragmentation, the two PLI-aware algorithms have 70% more for the last load point of the EON topology. For the USA topology in

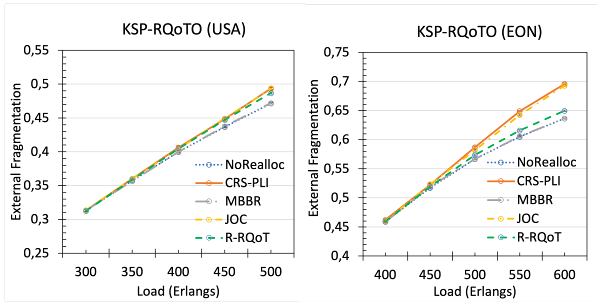

Figure 15 – External fragmentation (KSP-RQoTO).

Fig. 15, the levels of external fragmentation did not obtain relevant differences. In the EON topology, the last two load points already show a difference in fragmentation between the reallocation algorithms dealing with fragmentation and those not.

Finally, Fig. 16 represents external fragmentation in the scenario with the MD-PC allocation algorithm. Depending on the load on the network, the reallocation algorithms are compared with each other and with MD-PC (without reallocation) in two different topologies. In the USA topology, as in some previous figures on fragmentation, the values did not distinguish significantly between the algo-

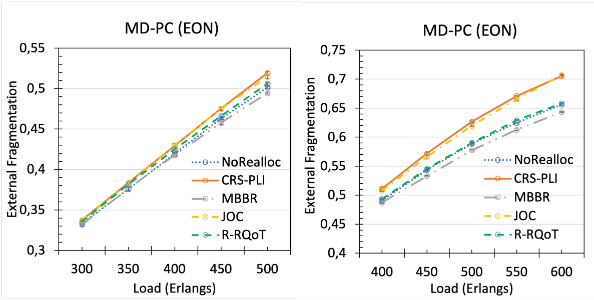

Figure 16 – External Fragmentation (MD-PC).

rithms. In the EON topology, with the increase in network load, the algorithms that deal with fragmentation started to present lower levels of external fragmentation compared to CRS-PLI and JOC, reallocation algorithms that aim to reduce the effects of physical layers and do not deal directly with the problem of fragmentation.

6.5 Percentage of circuits by modulation

The following graphs represent the percentage of modulation used by the circuits in the scenario considering the JOC reallocation algorithm applied to the KSP-RQoTO allocation algorithm. The objective of these graphs is to show which modulation was most used by the circuits, knowing that depending on the modulation choice strategy adopted, it will impact the reallocation process to be carried out. Rerouting a circuit, for example, can result in a more spectrally-efficient modulation choice, optimizing spectrum use. Figures 17 and 18 represent the percentage of circuits per modulation format.

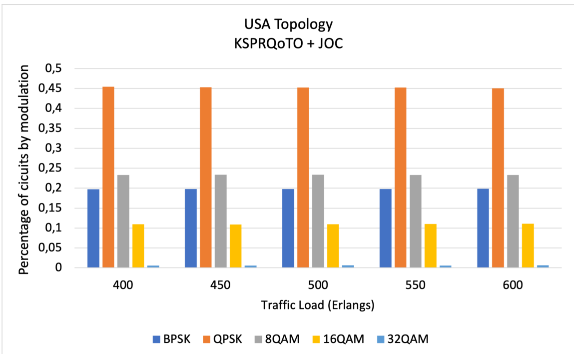

Figure 17 – Percentage of circuits by modulation use in the USA topology.

According to Fig. 17, the most used modulation at all load points was QPSK, followed by 8QAM and BPSK. QPSK modulation is used in approximately 45% of the network circuits as it is the most spectrally efficient in meeting the QoT requirements of the circuits and route distance. About 20% of circuits used QPSK modulation for the same reasons.

Fig. 18 shows the percentage of circuit per modulation for the EON topology of the KSP-RQoTO scenario using the JOC algorithm. Just like Fig. 17, QPSK modulation was the most used, but with a significant increase in the use of 8QAM modulation, representing more than 35% of use in

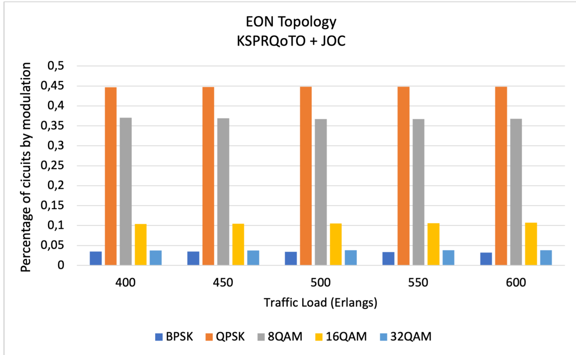

Figure 18 – Percentage of circuits by modulation use in the USA topology.

all load points on the network.

7. CONCLUSION

In this article, a circuit reallocation algorithm was proposed to reduce physical layer effects to fulfill imminent blocking requests. The proposed algorithm was applied in different allocation algorithm scenarios and compared with other reallocation algorithms, one for defragmentation and two also aware of physical layer effects. The difference in the contribution of this work is that, in addition to avoiding blocking requests that are imminently blocking, it chooses a single circuit to reallocate per execution of the algorithm. The only reallocated circuit will make it possible to fulfill the request and avoid blocking. Furthermore, the algorithm uses make-before-break traffic migration techniques to reroute circuits and push-pull to reassign spectrum.

In all scenarios evaluated, the proposal's performance was superior regarding bandwidth and circuit-blocking probability. The proposed algorithm contributed to considerably increasing traffic admission into the network, preventing imminent blocking requests from being blocked by reallocating a single circuit per process. The idea of reallocating the minimum circuit per process significantly reduces the complexity of the reallocation algorithm and the costs of operating on the network, as changes will be minimal.

ACKNOWLEDGEMENT

This work was developed with partial support from the Conselho Nacional de Desenvolvimento Tecnológico (CNPQ) and the Fundação de Amparo à Pesquisa do Piauí (FAPEPI).

REFERENCES

[1] Bijoy Chand Chatterjee, Nityananda Sarma, and Eiji Oki. "Routing and Spectrum Allocation in Elastic Optical Networks: A Tutorial". In: *IEEE Communications Surveys and Tutorials* 17.3 (2015), pp. 1776–1800. DOI: 10.1109/COMST.2015.2431731. URL:

https://doi.org/10.1109/COMST.2015.2431731.

[2] B. C. Chatterjee, S. Ba, and E. Oki. "Fragmentation Problems and Management Approaches in Elastic Optical Networks: A Survey". In: *IEEE Communications Surveys Tutorials* 20.1 (Firstquarter 2018), pp. 183–210. ISSN: 1553-877X. DOI: 10.1109/COMST.2017.2769102.

[3] M. Zhang, W. Shi, L. Gong, W. Lu, and Z. Zhu. "Bandwidth defragmentation in dynamic elastic optical networks with minimum traffic disruptions". In: *2013 IEEE International Conference on Communications (ICC)*. June 2013, pp. 3894–3898. DOI: 10.1109/ICC.2013.6655165.

[4] M. Zhang, C. You, H. Jiang, and Z. Zhu. "Dynamic and Adaptive Bandwidth Defragmentation in Spectrum-Sliced Elastic Optical Networks With Time-Varying Traffic". In: *Journal of Lightwave Technology* 32.5 (Mar. 2014), pp. 1014–1023. ISSN: 0733-8724. DOI: 10.1109/JLT.2013.2296781.

[5] H. Beyranvand and J. A. Salehi. "A Quality-of-Transmission Aware Dynamic Routing and Spectrum Assignment Scheme for Future Elastic Optical Networks". In: *Journal of Lightwave Technology* 31.18 (Sept. 2013), pp. 3043–3054. ISSN: 0733-8724. DOI: 10.1109/JLT.2013.2278572.

[6] S. Araújo, A. Soares, A. Fontinele, D. R. Campelo, J. V. d. R. Jênior, and Ê. Barbosa. "Circuit Reallocation Strategy Aware of the Physical Layer Effects for Elastic Optical Networks". In: *2018 IEEE Symposium on Computers and Communications (ISCC)*. June 2018, pp. 00970–00975. DOI: 10.1109/ISCC.2018.8538583.

[7] Selles Araújo, Jurandir Lacerda, Alexandre Fontinele, Érico Leão, José Reis Júnior, and André Soares. "Physical Layer-Aware Circuit Reallocation to Prevent Request Blocking in Elastic Optical Networks". In: *Anais do XLI Simpósio Brasileiro de Redes de Computadores e Sistemas Distribuídos*. Brasília/DF: SBC, 2023, pp. 295–308. DOI: 10.5753/sbrc.2023.489. URL: https://sol.sbc.org.br/index.php/sbrc/article/view/24546.

[8] A. G. Rahbar. "Review of Dynamic Impairment-Aware Routing and Wavelength Assignment Techniques in All-Optical Wavelength-Routed Networks". In: *IEEE Communications Surveys Tutorials* 14.4 (Fourth 2012), pp. 1065–1089. ISSN: 1553-877X. DOI: 10.1109/SURV.2011.101911.00023.

[9] C. V. Saradhi and S. Subramaniam. "Physical layer impairment aware routing (PLIAR) in WDM optical networks: issues and challenges". In: *IEEE Communications Surveys Tutorials* 11.4 (Fourth 2009), pp. 109–130. ISSN: 1553-877X. DOI: 10.1109/SURV.2009.090407.

[10] P. Poggiolini and Y. Jiang. "Recent Advances in the Modeling of the Impact of Nonlinear Fiber Propagation Effects on Uncompensated Coherent Transmission Systems". In: *IEEE/OSA Journal of Lightwave Technology* 35.3 (2017), pp. 458–480. DOI: 10.1109/JLT.2016.2613893.

[11] P. Johannisson and E. Agrell. "Modeling of Nonlinear Signal Distortion in Fiber-Optic Networks". In: *Journal of Lightwave Technology* 32.23 (Dec. 2014), pp. 4544–4552. ISSN: 0733-8724. DOI: 10.1109/JLT.2014.2361357.

[12] Tatsumi Takagi, Hiroshi Hasegawa, Ken-ichi Sato, Yoshiaki Sone, Akira Hirano, and Masahiko Jinno. "Disruption Minimized Spectrum Defragmentation in Elastic Optical Path Networks that Adopt Distance Adaptive Modulation". In: *37th European Conference and Exposition on Optical Communications*. Optica Publishing Group, 2011, Mo.2.K.3. DOI: 10.1364/ECOC.2011.Mo.2.K.3. URL: https://opg.optica.org/abstract.cfm?URI=ECOC-2011-Mo.2.K.3.

[13] Selles Araújo, Ênio Barbosa, José Reis Júnior, and André Soares. "R-RQoT: Uma Nova Estratégia de Realocação de Circuito Ciente dos Efeitos de Camada Física para Redes Ópticas Elásticas". In: *Anais do XXXVI Simpósio Brasileiro de Redes de Computadores e Sistemas Distribuídos*. Campos do Jordão: SBC, 2018, pp. 1103–1116. DOI: 10.5753/sbrc.2018.2481. URL: https://sol.sbc.org.br/index.php/sbrc/article/view/2481.

[14] Chao Wang, Gangxiang Shen, and Limei Peng. "Protection lightpath-based hitless spectrum defragmentation for distance adaptive elastic optical networks". In: *Opt. Express* 24.5 (Mar. 2016), pp. 4497–4511. DOI: 10.1364/OE.24.004497. URL: http://www.opticsexpress.org/abstract.cfm?URI=oe-24-5-4497.

[15] S. Ba, B. C. Chatterjee, and E. Oki. "Defragmentation Scheme Based on Exchanging Primary and Backup Paths in 1+1 Path Protected Elastic Optical Networks". In: *IEEE/ACM Transactions on Networking* 25.3 (June 2017), pp. 1717–1731. ISSN: 1063-6692. DOI: 10.1109/TNET.2017.2650212.

[16] Rana Kumar Jana, Bijoy Chand Chatterjee, Abhishek Pratap Singh, Anand Srivastava, Biswanath Mukherjee, Andrew Lord, and Abhijit Mitra. "Machine learning-assisted nonlinear-impairment-aware proactive defragmentation for C+L band elastic optical networks". In: *Journal of Optical Communications and Networking* 14.3 (2022), pp. 56–68. DOI: 10.1364/JOCN.440214.

[17] Enrique Dávalos, José-Luis Enciso, Nicolás Silva, Juan Pinto-Ríos, and Ariel Leiva. "Triggering strategy for defragmentation process in Elastic Optical Networks using Machine Learning techniques". In:

ICT Express 9.5 (2023), pp. 890–895. ISSN: 2405-9595. DOI: https://doi.org/10.1016/j.icte.2023.01.008. URL: https://www.sciencedirect.com/science/article/pii/S2405959523000085.

[18] F. Cugini, F. Paolucci, G. Meloni, G. Berrettini, M. Secondini, F. Fresi, N. Sambo, L. Poti, and P. Castoldi. "Push-Pull Defragmentation Without Traffic Disruption in Flexible Grid Optical Networks". In: *Journal of Lightwave Technology* 31.1 (Jan. 2013), pp. 125–133. ISSN: 0733-8724. DOI: 10.1109/JLT.2012.2225600.

[19] Roberto Proietti, Chuan Qin, Binbin Guan, Yawei Yin, Ryan P. Scott, Runxiang Yu, and S. J. B. Yoo. "Rapid and complete hitless defragmentation method using a coherent RX LO with fast wavelength tracking in elastic optical networks". In: *Opt. Express* 20.24 (Nov. 2012), pp. 26958–26968. DOI: 10.1364/OE.20.026958. URL: http://www.opticsexpress.org/abstract.cfm?URI=oe-20-24-26958.

[20] Eiji Oki and Bijoy Chand Chatterjee. "Performance of Defragmentation Approach Based on Route Partitioning in 1+1 Protected Elastic Optical Networks". In: *2023 23rd International Conference on Transparent Optical Networks (ICTON)*. 2023, pp. 1–4. DOI: 10.1109/ICTON59386.2023.10207346.

[21] Enrique J. Dávalos, Matilde F. Romero, Sergio M. Galeano, Diego A. Báez, Ariel Leiva, and Benjamín Baran. "Spectrum Defragmentation in Elastic Optical Networks: Two Approaches With Metaheuristics". In: *IEEE Access* 7 (2019), pp. 119835–119843. DOI: 10.1109/ACCESS.2019.2937032.

[22] Alexandre Fontinele, Iallen Santos, and Juarez Nolêto Neto and Divanilson R. Campelo and André Soares. "An Efficient IA-RMLSA Algorithm for Transparent Elastic Optical Networks". In: *Computer Networks* 118 (2017), pp. 1–14. DOI: 10.1016/j.comnet.2017.03.003. URL: https://doi.org/10.1016/j.comnet.2017.03.003.

[23] Alexandre Fontinele, Iallen Santos, Jurandir Lacerda Jr., André Soares, José Monteiro, and Divanilson Campelo. "Alocação de Espectro com Redução de Interferências entre Circuitos em Redes Ópticas Elásticas". In: *Anais do XXXVI Simpósio Brasileiro de Redes de Computadores e Sistemas Distribuídos*. Campos do Jordão: SBC, 2018, pp. 561–574. DOI: 10.5753/sbrc.2018.2442. URL: https://sol.sbc.org.br/index.php/sbrc/article/view/2442.

AUTHORS

Selles Araújo received his B.Sc. and M.Sc. degree in computer science in 2016 and 2019, respectively, at Federal University of Piauí, Teresina, Brazil. He is a Ph.D. candidate in the Post-Graduate Program in Computer Science at Federal University of Maranhão and Federal University of Piaui Association. He has been a professor at the Federal Institute of Education, Science and Technology of Piauí, Paulistana, Brazil, since 2019. His research includes optical networks, multicore fiber, circuit reallocation, physical layer, and performance evaluation.

Jurandir Lacerda Jr. received his B.Sc. and M.Sc. degree in computer science from the Federal University of Piauí, Teresina, Brazil, in 2013 and 2017, respectively. He is a Ph.D. degree in computer science at Federal University of Maranhão, São Luis, Brazil. He has been a professor at the Federal Institute of Education, Science and Technology of Piauí, Corrente, Brazil, since 2014. In addition, he is a member of Distributed Systems and Computer Network Laboratory (DiSNeL) at UFPI. His research includes optical networks, elastic optical networks, multicore fiber, network survivability, and resource allocation.

Alexandre Fontinele received the B.Sc. degree and M.Sc. degree in computer science from the Federal University of Piauí, Teresina, Brazil, in 2014 and 2016, respectively. He is a Ph.D. degree in computer science at Centro de Informática (CIn) of Federal University of Pernambuco, Recife, Brazil. He is a member of Distributed Systems and Computer Network Laboratory (DiSNeL). His research interests are optical networks, physical layer, resource allocation, and network performance evaluation.

Érico Leão received the B.Sc. degree in computer science from Federal University of Piauí (UFPI), Teresina, Brazil, in 2005; M.Sc. degree in computer engineering from Federal University of Rio Grande do Norte, Natal, Brazil, in 2007, and the Ph.D. degree in informatics engineering at Faculty of Engineering of the University of Porto, Porto, Portugal, in 2016.

Since 2009, he has been an Associated Professor with the Department of Computing, UFPI, Brazil. His current research interests include wireless sensor networks, real-time communication, large-scale applications and network simulation issues.

José Valdemir d. Reis Jr. received the B.Sc. degree in computer science in 2006 from the Federal University of Piauí, Teresina, Brazil; and the M.Sc. and Ph.D. degree in electrical engineering with emphasis on telecommunications in 2009 and 2015, respectively, at University of São Paulo, São Carlos, Brazil. In 2009, he joined the Teresina Technical College at the Federal University of Piauí, where he is a Professor of Computer Science. His current research interests include applications of intelligence systems for communications, smart sensors, evolutionary computation and internet of things.

André Soares received the B.Sc. degree in computer science in 2001 from the Federal University of Piauí (UFPI), Teresina, Brazil; M.Sc. degree in computer network in 2004 from the University of Salvador, Salvador, Brazil; and Ph.D. degree in computer science in 2009 from the Federal University of Pernambuco, Recife, Brazil. He is a professor in the Department of Computation at UFPI. Professor André Soares coordinates the Distributed Systems and Network Computer Laboratory (DiSNeL) at UFPI. Currently, his research interest includes topics like optical networks, survivability, resource allocation, and software defined network.

