Physical Layer-Aware Circuit Reallocation to Prevent Request Blocking in Elastic Optical Networks

Selles Araújo[1], Jurandir Lacerda[1], Alexandre Fontinele[1], Érico Leão[1], José V. dos Reis Júnior[1], André Soares[1]

[1] Departamento de Computação – Universidade Federal do Piauí (UFPI)
Teresina – PI – Brazil

sellesgustavo@gmail.com, andre.soares@ufpi.edu.br

Resumo. *This paper proposes a new circuit reallocation algorithm that considers the effects of physical layer in transparent elastic optical networks, called Just One Circuit Reallocation (JOC).The JOC algorithm reallocates just one already established circuit to avoid the blocking of new circuit request 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 (MBBr). The reallocation algorithms are evaluated under the bandwidth blocking probability (BBP), circuit blocking probability (CBP) and the number of reallocated circuits (NRC) for USA and EON topologies. Besides, 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 exhibits better performance than the CRS-PL, R-RQoT and MBBr algorithms with regard to BBP, PBC and NRC. In terms of BBP, our algorithm presented minimum reductions of approximately 65.36% e 55.6% for the USA and EON topology, respectively.*

1. Introduction

Elastic Optical Networks (EONs) have become a promising alternative for the future of optical networks. EONs are more efficient in resource utilization compared to traditional networks that provide channels with fixed wavelengths. Efficiency is achieved through the use of Orthogonal Frequency Division Multiplexing (OFDM) technology, allowing the division of the optical spectrum into small frequency ranges and thus providing circuit accommodation more fairly [Chatterjee et al. 2015].

The Routing, Modulation Level and Spectrum Assignment (RMLSA) problem must be solved for the establishment of optical circuit in the EONs [Chatterjee et al. 2015]. For each circuit request, an RMLSA algorithm defines the route, selects the appropriate modulation format and chooses a set of contiguous and continuous slots. The spectrum contiguity constraint requires that the slots be adjacent in each link of the route. Besides, the continuity constraint requires that the assigned slot be the same along the whole route. Both constraints must be attended to establish the optical circuit [Chatterjee et al. 2018].

The spectrum fragmentation is another common problem in EONs, especially under dynamic traffic. The fragmentation is caused by the successive establishments and finished of circuits in the network [Chatterjee et al. 2018]. The fragmentation consists in the distribution of small intervals of free slots without contiguity in the links, eventually provoking the circuit blocking. Such request blocking can be minimized from the defragmentation algorithm that typically reallocates some already active circuits to make the spectrum contiguous. [Zhang et al. 2013, Zhang et al. 2014].

In addition to the mentioned problems, it is necessary that a circuit has acceptable transmission quality (Quality of Transmission - QoT) to operate in the network. This acceptability is the correct interpretation of the optical signal at the destination, as it undergoes degradation as it propagates. Degradation occurs due to Physical Layer Imperfections (PLI) and can make communication impossible, thus generating circuit blocking. These types of blocks related to QoT can be mitigated or even avoided by reallocating active circuits in the network, object of this work [Araújo et al. 2018].

In this paper, a PLI-aware circuit reallocation algorithm, called Just One Circuit Reallocation (JOC), is proposed. The JOC algorithm is initiated when there is a potential blocking due to unacceptable QoT. Thus, it is sought to reallocate only one already established circuit to avoid the blocking of the new circuit request due to unacceptable QoT. In general, the reallocation of just one established circuit allows the new request to be attended with acceptable QoT. The JOC algorithm is compared to three other circuit reallocation algorithms. We carried out simulation study to analyze the bandwidth blocking probability (BBP), circuit blocking probability (CBP) and number of reallocated circuits (NRC). The topologies used were the USA and EON.

This paper is organized as follows. Section 2 presents the main physical layer impairments and their concepts. The problem of circuit reallocation aware of PLI and its characteristics are presented in Section 3. The related works are presented in Section 4. The JOC algorithm is proposed in Section 5. In Section 6 a performance evaluation study is made comparing the proposed algorithm to three other circuit reallocation algorithms: CRS-PL, R-RQoT and MBBr. Finally, the conclusions are presented in Section 7.

2. Physical Layer Impairments

In this paper, we use the physical layer model proposed in [Johannisson and Agrell 2014] in which the authors use the Optical Signal to Noise Ratio (OSNR) to measure the QoT of the optical circuits. The physical layer impairments considered in this model are amplified spontaneous emission (ASE), Auto phase modulation (SPM), cross phase modulation (XPM), and four-wave mixing (FWM) noises. These effects are also considered in other works in the literature [Poggiolini and Jiang 2017], [Habibi and Beyranvand 2019]. The hypotheses assumed related to physical layer are by following the model used in [Fontinele et al. 2017].

According to [Johannisson and Agrell 2014], [Yan et al. 2015], the OSNR calculation for circuit i, using a route r_i is given by

$$OSNR_i = \frac{I}{I_{ASE} + I_{NLI}}, \tag{1}$$

where I is the Power Spectral Density (PSD) of circuit i. $I = P_{TR}/\Delta_f$, in which P_{TR} is the signal power of i and Δ_f is the circuit bandwidth. I_{ASE} is the ASE noise PSD, and I_{NLI} is the PSD of the nonlinear interference (NLI). The PSD of the ASE noise is given by

$$I_{ASE} = \sum_{l \in r_i} N_l I^{l,s}_{ASE}, \tag{2}$$

where N_l is the number of spans of link l. Span is a link segment composed by an optical fiber and an amplifier equipment. $I^{l,s}_{ASE}$ is ASE noise in a single span of the link l, given by

$$I^{l,s}_{ASE} = Fhv(G_{AMP} - 1), \tag{3}$$

where F is the amplifier's noise figure (NF), h is Planck's constant, v is the light frequency and G_{AMP} is the optical amplifier gain. The total PSD of the nonlinear interferences (SPM, XPM, FWM) is given by

$$I_{NLI} = \sum_{l \in r_i} N_l I^{l,s}_{NLI}, \tag{4}$$

where $I^{l,s}_{NLI}$ is the PSD of the nonlinear interferences in a single span of the link l. $I^{l,s}_{NLI}$ is expressed by

$$I^{l,s}_{NLI} = \frac{3\gamma^2 I^3}{2\pi\alpha|\beta_2|}\left(\text{arcsinh}\left(\frac{\pi^2|\beta_2|}{2\alpha}B_i^2\right) + \xi\right), \tag{5}$$

where γ is the fiber nonlinear coefficient, β_2 is the fiber dispersion parameter, α is optical fiber loss, B_i is the circuit i bandwidth, and ξ is given by

$$\xi = \sum_{j} \ln\left[\frac{\left(\Delta_{f_{ij}} + \frac{B_j}{2}\right)}{\left(\Delta_{f_{ij}} - \frac{B_j}{2}\right)}\right]. \tag{6}$$

where j is another circuit using link l (which causes interference in circuit i). $\Delta_{f_{ij}}$ is the spacing from the central frequency between circuits i and j. B_j is the circuit j bandwidth.

The OSNR level is calculated for each new circuit request. In accordance with [Fontinele et al. 2017], a new optical circuit is established if and only if all the following requirements are met: i) availability of a free, contiguous, and continuous spectrum in the chosen route; ii) acceptable QoT to the candidate circuit, and iii) maintenance of an acceptable QoT for all other circuits already active in the network while the new optical circuit is serviced. Based on this model, there are three types of blocking. The first is the blocking due to the unavailability of a free spectrum that supports the bandwidth requested by the new optical circuit. This type of blocking occurs due to the spectrum fragmentation or the Absence of Free Spectrum (AFS) in the selected route. The second type of blockage is caused by an inadequate QoT for the new optical circuit (QoTN). The third type of blockage is caused by an inadequate QoT for the other optical circuits already active in the network (QoTO).

3. Circuit Reallocation aware of PLI

The circuit reallocation process allows the reorganization some or all established circuits to achieve specific objectives. Initially, different authors proposed new reallocation algorithms aiming to reduce the spectrum defragmentation. In this case, the circuit reallocation tries to reorganize the optical spectrum to obtain contiguous frequency slots, avoiding that requests are blocked by fragmentation [Zhang et al. 2014]. Recently, in addition to defragmenting the spectrum, the reallocation process has been used aiming to reduce the blocking caused unacceptable QoT [Araujo et al. 2018, Araújo et al. 2018].

It is required a new RMLSA solution that respects the QoT requirements to carry out the reallocation of the selected circuit. This problem was presented in [Araujo et al. 2018] and will be referred to in this article as Circuit Reallocation aware of PLI (CR-PLI).

The defragmenting the spectrum and CR-PLI are similar problems. The former problem seeks only to reduce spectrum fragmentation. On the other hand, the latter problem consists of reallocating already established circuits to avoid the blocking related inadequate QoT (i.e., QoTN or QoTO). Furthermore, depending on the heuristic adopted to solve the CR-PLI problem, fragmentation is also reduced.

Figure 1 exemplifies the CR-PLI problem. In this example, it is considered a network with 6 nodes and 7 links. The current state of the network in Figure 1(a) is composed of 3 established circuits (C1, C2, and C3) with their characteristics (modulation format, modulation threshold, and OSNR value). Considering also the scenario of Figure 1(a), it is not possible to establish C4 (new circuit request) on route C-B-E. The blocking of the circuit C4 is due to the interference of the already established circuits (C1 and C2) that share the links C-B and B-E. Therefore, the interference caused by the circuits C1 and C2 become the QoT of the circuit C4 unacceptable (OSNR equal to 19.4dB), less than the modulation threshold of 21dB, causing a blockage of the QoTN type.

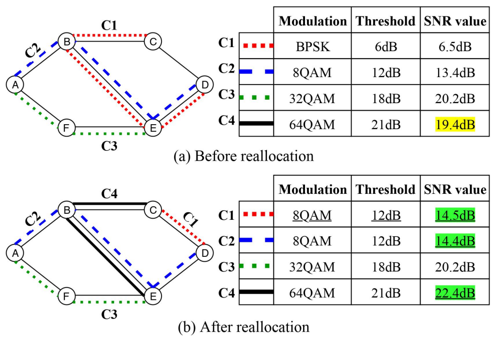


Figura 1. Example of CR-PLI problem. Network scenario (a) before and (b) after circuit reallocation to reduce blocking due to inadequate QoT.

Figure 1(b) illustrates a network scenario after reallocation of circuit C1. In this case, The circuit C1 has been moved from route C-B-E-D to route C-D. The relocation of circuit C1 was necessary to reduce the interference on the links of route C-B-E-D. This change reduces the interference of the already established circuits (C1 and C2) in new circuit requests (C4). In this example of Figure 1 (b), the interference is reduced, allowing the establishment of C4, with OSNR equal to 22.4 dB. This OSNR value is higher than the C4 modulation threshold (21 dB), resulting in acceptable QoT.

1. **When**: moment and/or periodicity of execution of the CR-PLI algorithm;
2. **Which**: circuits chosen for reallocation;
3. **How**: to define the new RMLSA solution to reallocation the chosen circuits. Besides, the technique of data traffic migration is defined in this step.

The Make-before-Break technique (MbB) [Takagi et al. 2011] traffic migration technique was considered in this work. The MbB technique consists of duplicating the circuit signal to be reallocated in a new route and then deactivating the primary circuit. The MbB changes the route of the circuits, providing greater flexibility of reallocation when compared to the other techniques that realize only spectral reassignment [Takagi et al. 2011, Cugini et al. 2013].

4. Related Work

The authors in [Takagi et al. 2011] propose the algorithm of reallocation based on the MbB technique, called Make-Before-Break strategy (MBBr). The MBBr algorithm is a hitless defragmentation algorithm that changes the route of already established circuits, using a different RMLSA solution. First of all, the MBBR identifies which the already established circuits that prevent the attend of a new circuit request. After this step, the MBBr migrates such already established circuits aiming to attend the circuit request that would be blocked previously. The migration of each circuit is performed using the MbB technique, also proposed by the same author [Takagi et al. 2011] and widely used in the literature.

The authors in [Zhang et al. 2013] detail the problem of defragmentation by listing their steps, and they propose new algorithms for the problem. The proposed algorithm uses the Most Frequently Used Slot First (MFUSF) and Highest Used Slot-Index First (HUSIF) strategy to choose 30% of the already established circuits for reallocation. The data traffic migrations are performed using the MbB technique.

The Truly Hitless is another circuit reallocation alternative that uses surviving scenarios and does not require traffic migration techniques [Wang et al. 2016, Ba et al. 2017]. In [Ba et al. 2017], for example, 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 change functions with the secondary ones to be reallocated. Thus, if a secondary circuit is chosen for reallocation, it is deactivated from the network and then reestablished using a different RMLSA solution. The change of the secondary circuit will have not to impact as the primary circuit continues transmitting the data.

It is important to note that the defragmentation algorithms seek to reduce fragmentation because it is the leading cause of blockages in the respective scenarios considered. However, these works do not take into account the physical layer impairment for the reallocation of the established circuits. Therefore, the defragmentation algorithms are not appropriate to solve the CR-PLI problem, since, in the scenario of this problem, inadequate QoT is the leading causes of blockages.

The authors in [Araujo et al. 2018] identified and presented the CR-PLI problem. In this same work, the authors proposed an algorithm called Circuit Reallocation for Block Reduction related to the QoT of the circuits (R-RQoT). The R-RQoT algorithm reallocates circuits whenever a blocking occurs by QoTN. The R-RQoT algorithm reallocates already established circuits that share the Links of the Blocked Route (LBR) to reduce the QoT interference in such links. The objective of R-RQoT algorithm is to avoid blocking of the circuits in the future that will use LBR. The selected established circuits are reallocated to the route with the least number of slots among the smaller k routes, providing load balancing. Traffic migration is performed using the MbB technique.

The authors in [Araújo et al. 2018] propose the called Circuit Reallocation Strategy - Physical Layer algorithm (CRS-PL). When the control plane identifies that some request can not be attended initially, this request is considered the Request of Imminent Blocking (RIB). Therefore, the CRS-PL algorithm analyses the established circuits that share links with the RIB, and it seeks to reallocate the circuits that most interferer in RIB until the RIB can be established. The entire process is performed in an auxiliary graph (in control plane) to represent the current state of the network. The circuit reallocations are carried out only if it is possible to attend the RIB. The selected established circuits are migrated to their disjoint routes by the MbB technique to reduce the interference due to the physical layer impairments.

5. Proposed Strategy

The Just One Circuit Reallocation (JOC) algorithm is proposed in this work to solve the CR-PLI problem. The JOC algorithm aims to reduce the QoT interferences caused among the already established circuits and a new optical circuit request. Besides, the JOC algorithm tries to mitigate the spectrum fragmentation. Such strategies decrease the overall blocking probability of the network. Figure 2 presents the operation of the proposed algorithm, as well as illustrates the moment in which it should be carried out.

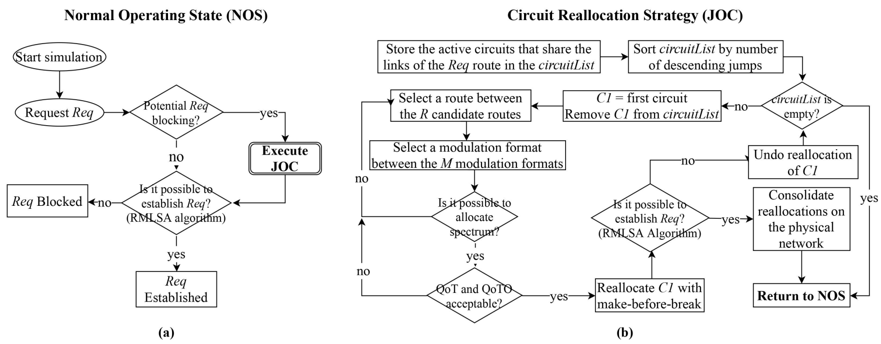


Figura 2. Flow diagram of the JOC circuit reallocation strategy.

The same way that CRS-PL algorithm, the JOC algorithm also considers the Request of Imminent Blocking (RIB) event. Figure 2(a) illustrates the operation of the JOC algorithm, always when a RIB event occurs. This potential blocking means that the new request will be blocked if the current state of the network is not modified. Thus, after the RIB event, the JOC algorithm is carried out in an auxiliary graph representing the current state of the network.

For explain the JOC algorithm, let us consider a given circuit request with an imminent blocking from source node S to destination node D, represented by $RIB(s, d)$. Assume that RMLSA solution to attend the $RIB(s, d)$ uses the route $route_{RIB}$. However, considering the actual network state, the RIB(s,d) cannot be established.

The first step of the JOC algorithm is to create the list $circuitList$ with already established circuits that share the links of the $route_{RIB}$, as shown in Figure 2(b). The $circuitList$ is arranged in descending order, considering of hop numbers of each already established circuits. The idea is to try first reallocate circuits with more hops of the $circuitList$. This behavior seeks to reduce QoT interference. Typically, circuits with more links achieve worse OSNR levels than circuits with few links. Therefore, in general, circuits that use a route with more links cause more QoT interference.

The second step of the JOC algorithm is to search a circuit C_i belong $circuitList$ to carry out its reallocation. The circuit C_i will be allocated if only this change allows the establishment of the RIB(s,d). Otherwise, the JOC algorithm analyses this possibility for the next circuit of $circuitList$. If the reallocation of circuit C_i occurs, JOC algorithm void the blocking of the $RIB(s, d)$ and it is finishing. It is important to note that the JOC algorithm reallocates just one circuit of $circuitList$. If the JOC algorithm does not reallocate any circuit of the $circuitList$, the RIB(s,d) is blocked.

The JOC algorithm uses the MbB technique to migrate the circuits. The MbB technique allows reallocate the circuit using a new route or new spectrum range. Besides, the MbB technique is commonly used in the literature. The route used for relocation the circuit C_i is chosen among the k-shortest paths of the Yen algorithm and the shortest route disjoint of the route used by circuit C_i. In this paper, we consider k=4.

6. Performance evaluation

The JOC algorithm was compared to the MBBr [Takagi et al. 2011], CRS-PL [Araújo et al. 2018] and the R-RQoT [Araujo et al. 2018] algorithms in terms of bandwidth blocking probability, circuit blocking probability and the number of reallocated circuits for USA and EON topologies (Fig. 3). The JOC, CRS-PL, and R-RQoT are reallocation algorithms that use the MbB technique and take into account the physical layer impairments in the reallocation process.

We carried out a performance evaluation study using the SNetS simulation tool (SLICE Networks Simulator) [Fontinele et al. 2017]. In the experiments, the optical circuits are established using the First-Fit algorithm to assign the spectrum. The K-Shortest Path Computation (KS-PC) [Beyranvand and Salehi 2013], Modified Dijkstra Paths Computation (MD-PC) [Beyranvand and Salehi 2013] and K-Shortest Path with Reduction of QoTO (KSP-RQoTO) [Fontinele et al. 2017] algorithms are used to select the route. We also consider the complete sharing (CS) algorithm [Wang and Mukherjee 2012] that assignment route and spectrum in a single step. These algorithms were chosen because they presented the best performance in terms of allocation of resources in the literature of the EONs.

A total of 100,000 requests are generated for each replication. The traffic load is uniformly distributed among all source-destination node pairs. The bandwidths of the circuits are uniformly distributed among 10, 40, 80, 100, 160, 200 and 400 Gbps. The generation of requests is a Poisson process of mean arrival rate λ, and the mean hold time of circuits is exponentially distributed with mean $1/\mu$. The network traffic intensity in Erlangs is given by ρ. For each simulation, 10 replications are performed with different random variable generation seeds. In all of the results presented in this paper, a confidence level of 95% was considered.

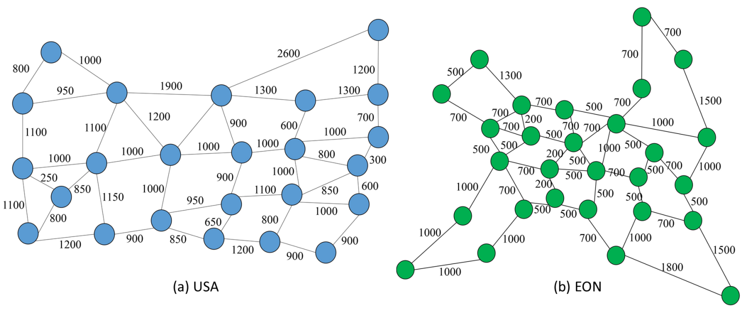
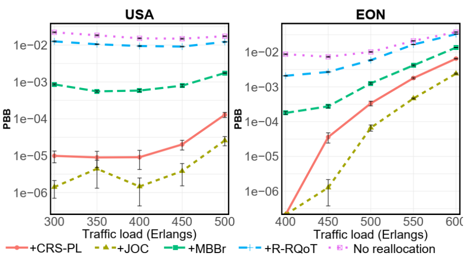
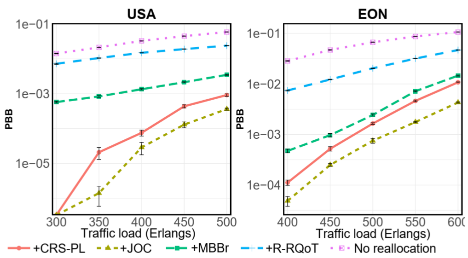


Figura 3. Topologies (a) USA (24 nodes) and (b) EON (28 nodes) with all bidirectional links. The value shown on each link of the topology indicates the link distance in km.

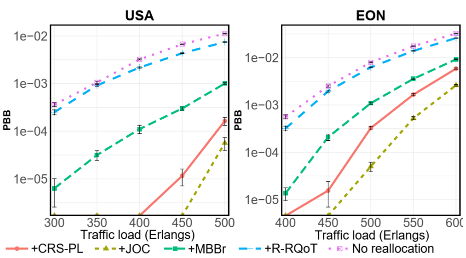
Figures 4(a), 4(b), 4(c), and 4(d) present the Bandwidth Blocking Probability (BBP) for the reallocation algorithms working respectively with the follow routing algorithms CS, KS-PC, KSP-RQoTO, and MD-PC. The First-Fit algorithm is used to spectrum assignment for all simulations. In such figures, reallocation algorithms are presented with the caption +JOC, +CRS-PL, +R-RQoT, and +MBBr, considering USA and EON topologies. For example, in Figure 4(a), the legend +JOC means that the routing algorithm is the CS and the reallocation algorithm is the JOC. It follows the same idea for other reallocation algorithms.



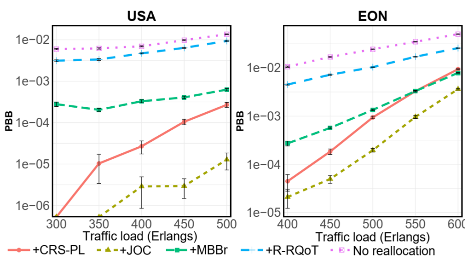
(a) Complete Sharing (CS)



(b) K Shortest Path Computation (KS-PC)



(c) K Shortest Path wih Reduction of QoTO (KSP-RQoTO)



(d) Modified Dijkstra Path Computation (MD-PC)

Figura 4. Bandwidth Blocking Probability achieved by (a) CS, (b) KS-PC, (c) KSP-RQoTO and (d) MD-PC algorithms working with circuit reallocation algorithms.

The JOC algorithm presents the best performance in terms of BBP when compared to the other algorithms, in Figure 4(a). Under 500 Erlangs in the USA topology, the JOC algorithm shows a PBB reduction of 79.92%, 98.52%, and 99.79% when compared to CRS-PL, MBBr, and R-RQoT algorithms, respectively. For EON topology under 600 Erlangs, JOC algorithm achieved respectively reductions of 63.07%, 82.27% and 92.69%

concerning the CRS-PL, MBBr, and R-RQoT algorithms.

In Figure 4(b), the JOC algorithm presented better performance compared to the other reallocation algorithms for all traffic loads. In the USA topology, for example, the JOC algorithm reduced 99.38% of the PBB compared to KS-PC (without reallocation) for the last load point analyzed. Also considering the last load point in the EON topology, the JOC algorithm presented 60.11% reduction compared to the CRS-PL.

In Figures 4(c) and 4(d) present the BBP for the reallocation algorithms when applied respectively to KSP-RQoTO and MD-PC, respectively. In the Figure 4(c), the JOC algorithm presents lower BBP results than the other reallocation algorithms, achieving a reduction of 65.36% and 55.6% when compared to CRS-PL under USA and EON topologies, respectively, for the last traffic load point.

In Figure 4(d), the JOC algorithm also presented better performance compared to its opponents for both topologies. For the last load point, in the USA topology, the reduction of JOC algorithm was 95.23% of BBP compared to the results of CRS-PL algorithm, whereas for the EON topology there was a decrease of 61.45%.

It is worth mentioning that the BBP values reductions are due to the reallocation of the circuit to provide higher admission of traffic in the network. Among the evaluated reallocation algorithms, the JOC algorithm presented the lower BBP reductions for all topologies and traffic loads, reallocating only one active circuit for each reallocation process, thus minimizing the changes in the physical network.

In addition to BBP, we analyze the JOC algorithm in terms of the Circuit Blocking Probability (CBP). The CBP can be decomposed into four components to differentiate the causes of the blockade. The components are blocking due to i) Absence of Free Spectrum (AFS), Spectrum Fragmentation (Frag), inadequate QoT for the new optical circuit (QoTN) and inadequate QoT for the other optical circuits already active in the network (QoTO).

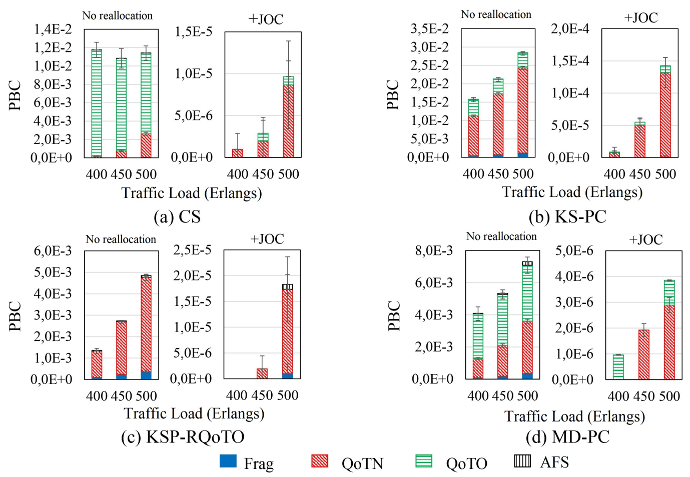


Figura 5. Circuit blocking probability components for the USA topology

Figure 6 shows the CBP components in scenarios with and without the application of the JOC algorithm, considering different RMLSA algorithms in the USA topology.

For each RMLSA algorithm studied, it is presented the results of CBP obtained with and without reallocation algorithm. In this study only the JOC algorithm is used. The results with and without JOC algorithm are plotted on the same scale. Besides, on the left side of each graphic, it is also presented an enlarged view of the JOC algorithm results. The CBP achieved to JOC algorithm is not zero in many cases. In such a scenario, the QoTN and QoTO components present the highest blocking probabilities. Besides, it is observed that the use of JOC algorithm produces reductions of QoTN and QoTO when compared to Frag and AEL components, under each traffic load analyzed.

Figure 6(a) presents the components of CBP for CS and CS+JOC algorithms. The CS+JOC algorithm reduced the values of QoTN and QoTO blockade when compared to CS algorithm. In numerical terms, the blockade was reduced from 0.0114% to 0.00000963% using +JOC, corresponding to a decrease of 99.92% blocking probability for the 500 Erlangs traffic load.

Likewise, the reductions of QoTN and QoTO blockings are also achieved when the JOC algorithm is used with KS-PC(KS-PC+JOC), in Figure 6(b). For each traffic load, the reallocation carried out by JOC algorithm decreased of the QoTN and QoTO blockings. Taking into account the 500 Erlangs load, only QoTN and QoTO blocking reductions were approximately 99.44% and 99.73% compared to without relocation scenario, respectively.

Figure 6(c) shows the results of the blocking components achieved when the KSP-RQoTO algorithm is used. The heuristic of the KSP-RQoTO algorithm avoids the occurrence of QoTO blocking. When the JOC algorithm is applied with KSP-RQoTO algorithm, the aim to prevent blocking QoTO is maintained, and therefore, the main reduction occurs in the QoTN component. The JOC algorithm reduced the CBP for all traffic load studied. Analyzing only QoTN blocking, the KSP-RQoTO is close to 0.0044058039 whereas for the KSP-RQoTO+JOC it is about 0.000016378, reducing the QoTN blocking by 99.63% to the higher traffic load.

The reallocations of the circuits carried out by JOC algorithm also decrease the impact of physical layer impairments when the MD-PC algorithm is used. The MD-PC+JOC algorithm achieved greater admission of circuit requests, using resources efficiently and improving network performance, Figure 6(d). Taking into account the QoTN and QoTO components under 500 Erlangs, the blocking reductions correspond to approximately 99.91%.

We also carry out a performance evaluation of the JOC algorithm considering the EON network topology. The components of CBP achieved to JOC algorithm was studied for different RMLSA algorithms (CS, KS-PC, KSP-RQoTO, and MD-PC).

Figure 6 shows the numerical results of the circuit blocking probability components for the EON topology. In Figure 6(a), the CS algorithm obtains CBP close to 2.0E-2 under 600 Erlangs, while CS+JOC algorithm achieves CBP lower than 1.0E-3. This reduction shows that the reallocations carried out by JOC algorithm are efficient in dealing with imminent blocking requests, contributing to the establishment of a circuit and, consequently, a reduction of blocking probability. Concerning blocking due to the physical layer impairments, the QoTN and QoTO components were respectively reduced by 94.18% and 98.57%, when compared to the CS algorithm without reallocation.

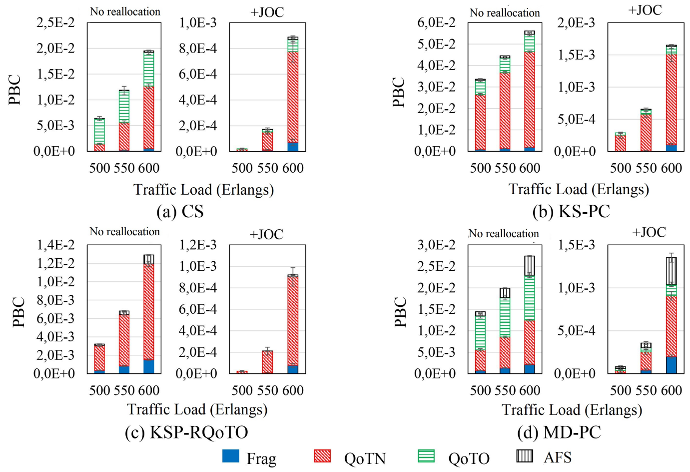


Figura 6. Circuit blocking probability components for the EON topology

Figure 6(b) shows the CBP components when the KS-PC and KS-PC+JOC algorithms are used. As can be observed in Figure 6(b), the JOC algorithm presents a considerable reduction in blocking due to the physical layer impairments. The QoTN blocking obtained by KS-PC corresponds to approximately 5.5E-2 whereas for the KS-PC+JOC it is about 2.0E-3. It is worth noting that there was a significant decline in all traffic loads considered, as observed in Figure 6(b).

In the EON topology, the KSP-RQoTO algorithm also avoids QoTO blocking. When the KSP-RQoTO algorithm works with JOC algorithm (Figure 6(c)), QoTN blocking suffered a reduction for all traffic load points. Under 600 Erlangs, the QoTN blocking decreases by 92.07% when the JOC algorithm is used together KSP-RQoTO.

The proposed algorithm is also efficient when applied in a scenario using the MD-PC algorithm. In Figure 6(d), the circuit blocking probability without and with the use of the JOC algorithm is presented. When the results of the MD-PC and the MD-PC+JOC are compared, it is observed that the QoTN and QoTO components suffered the most significant blocking reductions due to JOC reallocations.

The number of reallocated circuits (NRC) is another critical metric to evaluate the performance of reallocation algorithms. This metric show how many circuits are redistributed in the same reallocation process. The calculation of NCR consists of the following:

$$\text{NCR}_m = \frac{\sum_1^{total} numberOfReallocatedCircuits}{total}.$$

The variable $total$ is the total number of relocation processes in each simulation (i.e. the number of times that the reallocation algorithm is executed). For each reallocation process, the number of reallocated circuits is summed and, at the end of the simulation, that value is divided by $total$ to obtain the NCR. Decrease the values of NCR means to reduce the number of changes in the network, also decreasing the circuit migration costs.

Figure 7 shows the NCR_a values of the reallocation strategies aware of physical layer imperfections for the topology USA. The values of NCR_a were obtained for the scenarios CS, KS-PC, KSP-RQoTO and MD-PC, considering different loads of traffic in the network.

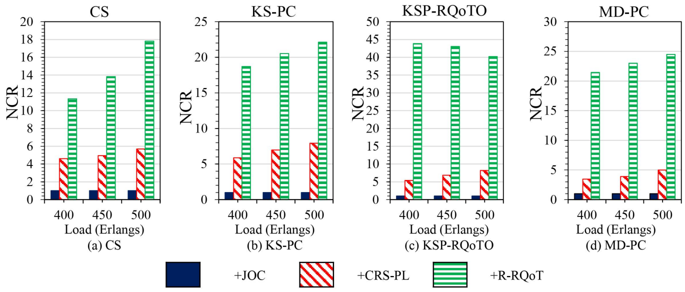


Figura 7. NCR$_a$ values for the USA topology in the scenario (a) CS, (b) KS-PC, (c) KSP-RQoTO and (d) MD-PC.

The Figure 7(a) presents the NCR$_a$ for the JOC, CRS-PL and R-RQoT strategies in the CS scenario. It is observed that the value of NCR$_a$ of the JOC is the lowest among the strategies evaluated for all load points. In Figure 7(b), the NCR$_a$ values also remain the same for the JOC, corresponding to at most 1 reallocated circuit per reallocation process.

The NCR$_a$ values of Figure 7(c) 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 NCR$_a$ was observed for the CRS-PL algorithm, the JOC remains with only 1 process reallocated circuit. The same occurs for the scenario of Figure 7(d), with the lowest value being of the JOC algorithm.

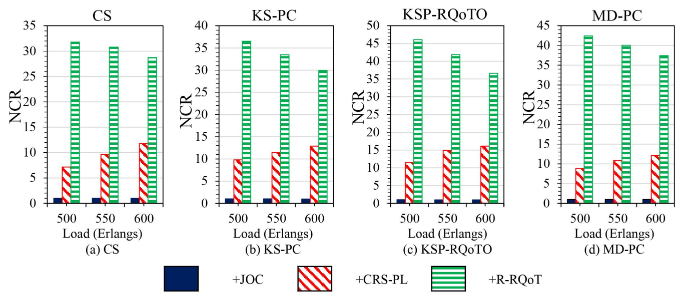


Figura 8. NCR$_a$ values for the EON topology in the scenario (a) CS, (b) KS-PC, (c) KSP-RQoTO and (d) MD-PC.

The NCR$_a$ metric also was evaluated in the different allocation algorithm scenarios for the EON topology. The evaluation was carried out under different loads in the network, as well as in the scenario of Figure 7. Thus, the numerical results of the NCR$_a$ metric for the EON topology are presented in Figure 8.

Figure 8(a) presents the values of NCR$_a$ when the PLI aware relocation strategies are applied in the CS. For each traffic load studied, the value of NCR$_a$ is approximately 1 for the +JOC algorithm. Similarly, in Figure 8(b) the +JOC algorithm achieved the lowest NCR$_a$ 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 1 circuit to avoid blocking requests, while the +CRS-PL algorithm required the rerouting of approximately 13 active circuits.

In Figure 8(c), the results of the NCR_a were observed when the considered 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 NCR_a value of 16 and 37 respectively, the +JOC has NCR_a equal to 1. As in Figure 8(c), the Figure 8(d) also has an NCR_a value of 1, while +CRS-PL has NCR_a close to 37 considering the last loading point.

The NCR_a values of the JOC algorithm are equal to 1 under different traffic loads is due to its heuristic that allows just 1 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. It is worth mentioning that the JOC and CRS-PL strategies reallocate circuits in order to meet the impending blocking request. The R-RQoT reallocates the circuit in order to avoid blocking future requests with characteristics similar to those blocked. Therefore, the different approach reflects on the expressive value of NCR_a for the R-RQoT algorithm.

7. Conclusion

In this paper, a PLI-aware circuit reallocation algorithm, called JOC (Just One Circuit Reallocation), was proposed. The use of the JOC algorithm contributes significantly to the reduction of blockages due to physical layer imperfections. For performance evaluation, JOC was compared to three other circuit relocation strategies of the literature in terms of bandwidth blocking probability (PBB), circuit block probability (PBC) and average number of circuit relocation (NCR_a). The results were obtained from computational simulations in two distinct network topologies, USA and EON.

In the USA topology, the JOC algorithm showed minimum PBB reductions of approximately 65.36% while for the EON topology it was 55.6%, mainly reducing QoTN and QoTO block. In addition, the performance of the proposed strategy was achieved by significantly reducing the average number of network reallocations in the network when compared to the other strategies. While the JOC algorithm reallocates a single circuit per process, the other algorithms reallocate on average at least ten circuits per process, considering the last load point and independent of topology.

Referências

Araujo, S., Barbosa, E., dos Reis Junior, J. V., and Soares, A. (2018). R-rqot: Uma nova estratégia de realocação de circuito ciente dos efeitos de camada física para redes Ópticas elásticas. *Simpósio Brasileiro de Redes de Computadores e Sistemas Distribuídos (SBRC)*.

Araújo, S., Soares, A., Fontinele, A., Campelo, D. R., d. R. Jênior, J. V., and Barbosa, (2018). Circuit reallocation strategy aware of the physical layer effects for elastic optical networks. In *2018 IEEE Symposium on Computers and Communications (ISCC)*, pages 00970–00975.

Ba, S., Chatterjee, B. C., and Oki, E. (2017). Defragmentation scheme based on exchanging primary and backup paths in 1+1 path protected elastic optical networks. *IEEE/ACM Transactions on Networking*, 25(3):1717–1731.

Beyranvand, H. and Salehi, J. A. (2013). A quality-of-transmission aware dynamic routing and spectrum assignment scheme for future elastic optical networks. *Journal of Lightwave Technology*, 31(18):3043–3054.

Chatterjee, B. C., Ba, S., and Oki, E. (2018). Fragmentation problems and management approaches in elastic optical networks: A survey. *IEEE Communications Surveys Tutorials*, 20(1):183–210.

Chatterjee, B. C., Sarma, N., and Oki, E. (2015). Routing and spectrum allocation in elastic optical networks: A tutorial. *IEEE Communications Surveys and Tutorials*, 17(3):1776–1800.

Cugini, F., Paolucci, F., Meloni, G., Berrettini, G., Secondini, M., Fresi, F., Sambo, N., Poti, L., and Castoldi, P. (2013). Push-pull defragmentation without traffic disruption in flexible grid optical networks. *Journal of Lightwave Technology*, 31(1):125–133.

Fontinele, A., Santos, I., Neto, J. N., Campelo, D. R., and Soares, A. (2017). An efficient IA-RMLSA algorithm for transparent elastic optical networks. *Computer Networks*, 118:1–14.

Habibi, M. and Beyranvand, H. (2019). Impairment-aware manycast routing, modulation level, and spectrum assignment in elastic optical networks. *IEEE/OSA Journal of Optical Communications and Networking*, 11(5):179–189.

Johannisson, P. and Agrell, E. (2014). Modeling of nonlinear signal distortion in fiber-optic networks. *Journal of Lightwave Technology*, 32(23):4544–4552.

Poggiolini, P. and Jiang, Y. (2017). Recent advances in the modeling of the impact of nonlinear fiber propagation effects on uncompensated coherent transmission systems. *IEEE/OSA Journal of Lightwave Technology*, 35(3):458–480.

Takagi, T., Hasegawa, H., i. Sato, K., Sone, Y., Hirano, A., and Jinno, M. (2011). Disruption minimized spectrum defragmentation in elastic optical path networks that adopt distance adaptive modulation. In *2011 37th European Conference and Exhibition on Optical Communication*, pages 1–3.

Wang, C., Shen, G., and Peng, L. (2016). Protection lightpath-based hitless spectrum defragmentation for distance adaptive elastic optical networks. *Opt. Express*, 24(5):4497–4511.

Wang, R. and Mukherjee, B. (2012). Spectrum management in heterogeneous bandwidth networks. In *2012 IEEE Global Communications Conference (GLOBECOM)*, pages 2907–2911.

Yan, L., Agrell, E., Wymeersch, H., Johannisson, P., Di Taranto, R., and Brandt-Pearce, M. (2015). Link-level resource allocation for flexible-grid nonlinear fiber-optic communication systems. *IEEE Photonics Technology Letters*, 27(12):1250–1253.

Zhang, M., Shi, W., Gong, L., Lu, W., and Zhu, Z. (2013). Bandwidth defragmentation in dynamic elastic optical networks with minimum traffic disruptions. In *2013 IEEE International Conference on Communications (ICC)*, pages 3894–3898.

Zhang, M., You, C., Jiang, H., and Zhu, Z. (2014). Dynamic and adaptive bandwidth defragmentation in spectrum-sliced elastic optical networks with time-varying traffic. *Journal of Lightwave Technology*, 32(5):1014–1023.