

Performance Evaluation of Non-Hitless Spectrum Defragmentation Algorithms in Elastic Optical Networks

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Abstract—Fragmentation in Elastic Optical Networks is an issue caused by isolated, non-aligned, and non-contiguous frequency slots that can not be used to allocate new connection request to the network, due to the optical layer restrictions imposed to the Routing and Spectrum Assignment (RSA) algorithms. To deal with this issue, several studies about Spectrum Defragmentation have been presented. In this work, we analyze the most important Non-Hitless Defragmentation Algorithms found in the literature, with proactive and reactive approaches that include rerouting and non-rerouting schemes, and compare their performance in terms of Blocking Probability, Entropy, and Bandwidth Fragmentation Ratio. Simulations results showed that the Fragmentation Aware schemes outperformed the other algorithms in low traffic load, but the Reactive schemes got better results in high traffic load.

Index Terms—Spectrum Defragmentation, EON, RSA

I. INTRODUCTION

The rising popularity of recent applications on the Internet that require a high bandwidth, like Video on Demand and others, are increasing the requirements of the current networks. To meet these demands, a more efficient use of the optical fibers is needed. Elastic Optical Networks (EON) [1] is a technology that achieve a more efficient use of the spectrum, because it fragments the spectral resources of the fiber channel, into little, width-constant spectral slices, called Frequency Slots (FS), that correspond to different optical wavelengths [2], and use an appropriate number of this FS to serve a connection request with just enough bandwidth, leaving more spectral resources available for future connections.

An essential problem in EON is the selection of the route, and spectral resources for a connection request arriving to the network, knowing as the problem of Routing and Spectrum Assignment (RSA) [2], [3], [4]. The RSA problem is a particular case of the Routing and Wavelength Assignment (RWA) [5], [6], [7], [8] scheme, that is used in the Wavelength Division Multiplexing (WDM) [9], [10], [11] technologies. The EON architecture imposes to the RSA problem three constraints: (1) the *wavelength continuity constraint*, that is the allocation of a connection, in the same wavelength on each link along the route, (2) the *spectrum contiguity constraint*, that is the allocation of a connection on contiguous FS on each link

along the route, and (3) the *spectral conflict constraint*, that is a connection allocated to a certain spectral resource, cannot overlap with the spectral resources of other connections.

The spectrum allocation of connections, requires available and contiguous FS (called slot-blocks) with a bandwidth of a few GHz or even smaller. The frequent setting up and tearing down of these connections can cause the Fragmentation of the Spectrum [6]. Spectrum Fragmentation is defined as the existence of available slot-blocks that are not aligned (different wavelength on the links along the route), nor contiguous (are not adjacent to each other) in the spectrum domain, meaning that, this slot-blocks are isolated, making it really hard to use them to allocate future connections. If the available slot-blocks cannot meet the require bandwidth of a connection request, or are not align in the spectrum, then this request will be rejected. For this reason, the defragmentation of the Spectrum is important to minimize the rejection of future connections. In the literature, several Defragmentation Algorithms were proposed. These algorithms can be split into two approaches: *proactive*, where the defragmentation is invoked without waiting for a new connection request, i.e. it takes evasive measures to avoid the fragmentation of the spectrum; and *reactive*, that are triggered when a new connection request arrives and would be blocked if no defragmentation is being made. Both of this approaches usually require necessary rerouting to accommodate the established connections, often causing traffic disruption. To address this issue, a defragmentation method that avoids disruption was proposed in [12], namely *Non-disruptive* or *Hitless Defragmentation* where the re-accommodation of the spectral resources of a connection happens while its traffic is still active. In this study only the Non-Hitless approaches are considered.

It is important to fully understand the advantages and disadvantages of both reactive and proactive approaches. However, to the best of our knowledge, an exhaustive analysis of these algorithms with their characteristics and performances has not been reported yet.

Contribution. As a first part of our work, we present an analysis of the different Non-Hitless Defragmentation Algorithms in EON, with both proactive and reactive approaches, that

include rerouting and non-rerouting schemes, presenting the results of several simulations with dynamic traffic in different scenarios on one network topology, comparing the results of different metrics in order to learn in which circumstances an algorithm outperforms the others.

The remainder of this work, is organized as follow: in Section II, the Defragmentation Problem in EON is presented, in Section III, we discuss the related works in the literature, in Section IV, we present the experimental environment where the simulations have been made, and in Section V we analyze the obtained results. Finally, in Section VI we conclude this paper, and present our future works.

II. DEFRAGMENTATION PROBLEM

In a dynamic environment in EON, the connections are setting up and tearing down at any time, and the resources that were being occupied by these connections, are now available to be assigned to future connection request. As the connections can require different bandwidths, this leads to the presence of little, and isolated slot-blocks, that are non-contiguous, nor contiguous in the spectrum, hence unusable for future connections. This is known as *Spectrum Fragmentation*. Due to the EON restrictions, the Spectrum Fragmentation leads to low utilization of the spectrum in the network and can cause the rejection of new connections requests. In the Fig. 1 a simple example of defragmentation is shown. In a network with three nodes, represented in Fig. 1 (a), with three bi-directional links with 5 FS each, suppose a connection request d with source in the node A , and destination node C , that requires 2 FS. As we can see in the spectrum usage illustrated in Fig. 1 (b), the link between A and C is a candidate route for d , because it has the right amount of available FS required by d , but these are not contiguous, i.e. d cannot be assigned to that route because it does not meet the contiguity restriction. The next candidate route, is from A to B , and then B to C . In this Figure we can see that both, the link between A and B , and the link between B and C , have the right amount of contiguous FS that d requires, but these slot-blocks are not aligned in the spectrum, i.e. this route does not meet the continuity restriction. Thus, even if the spectrum have available resources, the connection request d will be rejected. But if we invoke a defragmentation algorithm, the occupied spectral resources would be re-organized, leaving available, contiguous and aligned FS to allocate future connections, as we can see in Fig. 1 (c).

The defragmentation algorithms can be analyzed in terms of control approaches and reconfiguration schemes. The control approaches can be split into two types:

- Proactive: These are the ones that are activated without waiting for the arrival of a new connection request, i.e. they take measures to leave enough resources available for future connections. A Fragmentation Aware RSA, or a periodic defragmentation scheme, can be considered as proactive approaches.
- Reactive: The reactive algorithms are triggered when a connection request cannot be allocated due to the

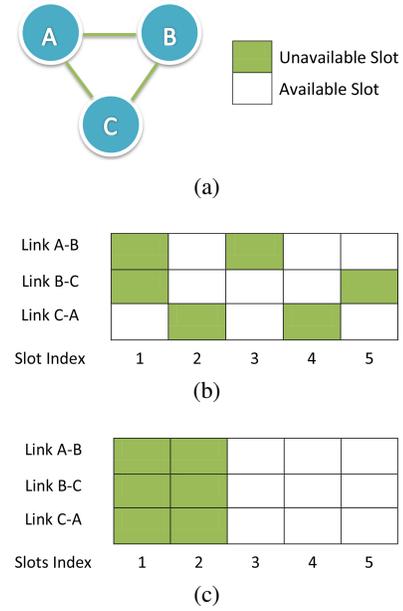


Fig. 1: Simple example of Defragmentation in EON

Spectrum Fragmentation, and the spectrum needs to be reconfigured to make enough room for this connection request.

On the other hand, the reconfiguration schemes are: non-rerouting and rerouting. In the non-rerouting scheme, when the connections are reconfigured, the index of its slot-blocks changes, but not its original route; and in rerouting, both the slot-blocks index and the original route can be modify.

In this work, we will study the Non-Hitless Defragmentation Algorithms, with reactive and proactive approaches that include rerouting and non-rerouting schemes.

III. NON-HITLESS DEFRAGMENTATION ALGORITHMS

In the literature, different strategies have been presented to address the defragmentation problem, and thus, minimize the Blocking Probability of the network due to Spectrum Fragmentation. Blocking Probability is a metric that measures the ratio between the blocked (rejected) connections, and the total requested connections in the network. In the next subsections, we address the different non-hitless defragmentation algorithms presented in the literature, split into proactive and reactive schemes. In the Fig. 2, a simple representation of the considered algorithms is shown, presenting the usage of the spectrum of the network in Fig. 1 (a), before and after a defragmentation algorithm is invoked.

A. Proactive Approaches

The proactive approaches are those where the a defragmentation is invoked to consolidate the spectrum (minimize the total required spectral resources for the existing connections) and minimize the rejection of future connection request. It can be an algorithm executed periodically to reconfigure

own original route, starting with the connections with the longer routes (Fig. 2 (g, h)). In [17], Zhang et. al. presented a proactive strategy to minimize the disruptions on the network. Here, each time a certain number of connections is terminated, the defragmentation is invoked, selecting a portion of all the established connections to be rerouted with a best-effort strategy. This algorithm is represented in Fig. 2 (i, j). This work is expanded in [18], where a more exhaustive study is presented to answer the questions: What to Reconfigure? When to Reconfigure? How to Reconfigure? and How to migrate traffic? Here, it is being studied the best combination of RSA algorithms for reconfiguration, and the best way to migrate traffic. Then, it is proposed an intelligent and adaptive selection of connections and the time of reconfiguration (Fig 2 (k, l)). In [19], Aibin et. al. presented a strategy of defragmentation, where the established connection with the longest holding time is constantly search for, to be rerouted to an optimal pair of route and slot-block. This strategy keeps the connections that will remain in the network for the longest time in the best possible state, so they would cause the least amount of conflicts with future connections request (Fig. 2 (m, n)).

Regarding the Fragmentation Aware RSA algorithms, in [20] Zhang et. al. presented a metric to measure the fragmentation of the network, called Network Fragmentation Ratio (NFR), where he tries to maintain the slot-blocks of bigger size available to accommodate future connections. Then he proposes an RSA algorithm based on NFR, where the route and the slot-blocks are selected according to the NFR of each candidate. In Fig. 2 (o) a connection request with source A and destination in B , that requires 2 FS, can be assigned in $A - C - B$, but choosing this solution will get a bigger NFR comparing to $A - B$, because it will use more slot-blocks, hence, increasing the NFR, this is why, the latter solution is selected (Fig. 2 (p)). In [21] Yin et. al. presented a *Fragmentation and Alignment Aware* RSA algorithm, where, before the assignment of a route and slot-block, to a connection request, the following is considered: the amount of slot-blocks that the connection will need, and the misalignment that this assignment will cause between the already available and aligned slot-blocks. An example of this algorithm is shown in Fig. 2 (q). Suppose a connection request d with source A , and destination B , that requires 2 FS. A candidate solution would be the assignation of d to the link $A - B$, but this will interfere with the existing alignment of the available slot-blocks in the three links, this is why, in Fig. 2 (r), d is allocated in $A - C - B$, where it does not cause any misalignment. This work was extended in [22], where they also presented a *congestion avoidance* strategy, that improves its performance in higher loads of traffic.

B. Reactive Approaches

In the reactive approaches, the defragmentation is triggered to allocate a connection request that would be blocked otherwise, usually by rerouting the established connections that will be in conflict with the selected route and slot-blocks for

TABLE I: Summary of the Non-Hitless Defragmentation Algorithms

| | Proactive | Reactive |
|---------------|---|---------------------------|
| Rerouting | Greedy [13] SP [13] MSGD [14] and [15] CBD [17] ATAR [18] DWD [19] | MBBR [23] |
| Non-rerouting | SDUIS [16] FA MNFR [20] FA PCF [21] FA RSA [22] FA CA RSA [22] | MCDA [24] SPRESSO [25] |

the new connection request. This necessary rerouting, usually cause disruptions in the network. To minimize this disruptions, Takagi et. al. presented in [23] a rerouting algorithm in a Make Before Break (MBBR) manner, where only if each one of all of the connections in conflict with the new connection request find an alternative route, then these are rerouted without releasing their original resources yet. Until all of the connections are established in their new route, and the resources of the old ones are released, then the new connection request can be allocated. The Fig. 2 (s, t) shows how the connections a and e had to be rerouted for d to be allocated. In [24], Yin et. al. proposed a strategy where a pair of route and slot-block, with the least number of established connections in conflict with a new connection request is searched. When this pair is found, the connections in conflict are reassigned on different slot-blocks, but in the same route, to give room for the new connection to be allocated (Fig. 2 (u, v)). Lastly, Castro et. al. in [25], presented a strategy where if enough FS are available in one of the shortest routes, the defragmentation is triggered, to find a set of already established connections, and then reassigned them on contiguous available FS, to make enough room for the connection to be allocated (Fig. 2 (w, x)).

The Table I presents a summary of the aforementioned defragmentation algorithms.

IV. EXPERIMENTATION

In order to analyze the Non-Hitless Defragmentation Algorithms, we made a series of Simulations in different scenarios to compare their performance. To make these simulations, we extended the RSA simulator EONS [26], adding features of Defragmentation, and the algorithms discussed.

The simulations were made with a 14-Node NSFNET topology (Fig. 3). For this topology, we considered a bandwidth of 4400 Ghz, where each link has 352 FS, and each FS has a bandwidth of 12,5 Ghz. The connections requests, with random source and destination, were generated according to a Poisson process. Each simulation run for a fixed time of 1000 units of time.

The Scenarios for the Simulations were the following:

- Scenario 1: Traffic Load Analysis. For low traffic loads we use 200 Erlang, and for high traffic loads, 700 Erlang. The holding time is constant and equal to 0.5% of the simulation time, and for each connection request, the number of FS is uniformly distributed between 2-16.
- Scenario 2: Holding Time Analysis. For short holding times, the holding time for each connection request is constant and equal to 0.1% of the simulation time, and for long holding times, the holding time for each connection request is constant and equal to 0.9% of the simulation time. The traffic load is 300 Erlang, and for each connection, the number of FS is uniformly distributed between 2-16.
- Scenario 3: Bandwidth of Connections Analysis. For the static case, the number of FS is constant and equal to 8, for each connection, and for the dynamic case, the number of FS for each connection is uniformly distributed between 2-12. The traffic load is 300 Erlang, and the holding time of each connection is constant and equal to 0.4% of the simulation time.

In order to evaluate and compare the performance of the considered algorithms, we use the following metrics:

- *Blocking Probability (BP)*: It is defined as the ratio between the blocked connections request versus the total of the requested connections .
- *Entropy*: To measure the level of the defragmentation in a link, we use the entropy as [27]:

$$UE_e = \frac{\sum_{FS \in e} UE_{FS}}{B} \quad (1)$$

Where the summation of UE_{FS} represents the amount of state changes of the FS in a link e , i. e. if a FS is available, and its neighbor is not, a change of state is registered, and it goes like this for all the FS along the link. A big amount of state changes in a link, means that the link is very fragmented. B represents the amount of FS per link. Then the entropy of the network is defined as:

$$UE_{Net} = \frac{\sum_{e \in E} UE_e}{|E|} \quad (2)$$

Where UE_e represents the entropy of each link, and $|E|$ the amount of links in the network.

- *Bandwidth Fragmentation Ratio (BFR)*: We define de BFR of a link as in [28]:

$$\lambda_e = \begin{cases} 1 - \frac{MaxBlocks(FS_e)}{B - sum(FS_e)} & sum(FS_e) < B \\ 0 & sum(FS_e) = B \end{cases} \quad (3)$$

where $MaxBlocks(FS_e)$ represents the size of the biggest slot-block available in e ; B is the number of FS per link, and $sum(FS_e)$ is the amount of unavailable FS

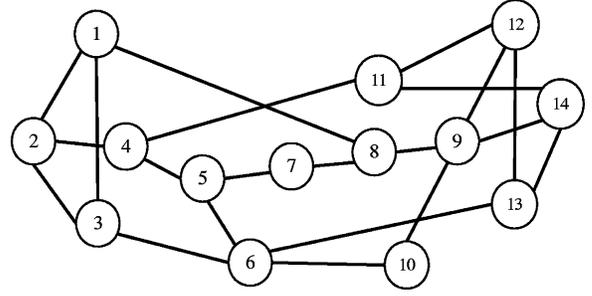


Fig. 3: 14-Node NSFNET Topology

in the link e . Then, the BFR of the network is defined as:

$$BFR_{Net} = \frac{\sum_{e \in E} \lambda_e}{|E|} \quad (4)$$

where E represents the set of links and $|E|$ is the amount of links in the network. This metric is similar to the one presented in [20].

All of the defragmentation algorithms, except for the Fragmentation Aware ones, were invoked over the RSA algorithm: FAR Random Fit. In this RSA, FAR [29] is the routing algorithm, where every node has a routing table of fixed routes for each destination node, and to select the route, the source node attempts all of the routes from its routing table in sequence, until the destination node is found; and the Spectrum Assignment algorithm is Random Fit [30] where this algorithm keeps track of all of the available slot-blocks, and when a connection request arrives, it picks randomly one of the slot-blocks available on the selected route that meets the connection requirements. For the proactive algorithms, the threshold selected, to call the defragmentation operation, was the same one proposed in their respective papers.

V. NUMERICAL RESULTS

In the Fig. 4 to 9 the obtained results on the Scenario 1 are shown, where we analyze the behavior of the algorithms under low and high traffic loads (200 and 700 Erlang respectively). In the Fig. 4 and 5 we can see that, effectively, every algorithm with defragmentation got a better BP, than the one without defragmentation, which implies a better use of the spectrum for the first ones, because they blocked less connections request. In low traffic loads, according to Fig. 4 the Fragmentation Aware (FA) RSA algorithms: FA-P-CF-RSA and FA-CA-RSA obtained a better performance than the other ones, but, in high traffic loads, as shown in Fig 5, the reactive algorithm FAR-RF-MCDA obtained a marginal advantage over the aforementioned algorithms. This happens because in high loads, the network becomes more congested, leaving little room for the “fragmentation awareness”, i.e. there are less options to optimally select the routes and slot-blocks to allocate the connections request.

According to the Entropy metric, in the Fig. 6 and 7 we can see that the FA algorithms: FA-P-CF-RSA and FA-CA-RSA, once again got better results. Also, the other FA algorithms got better results, like in the BP metric with low traffic loads. This does not happen in high traffic loads, where the FAR-RF-MCDA algorithm got a better performance in BP with high traffic load, but did not get the best performance in the Entropy. The reason for this is that the FA algorithms try to maintain the spectrum in a good state constantly, carefully selecting the routes and slot-blocks to this end, thus, getting a low entropy. Unlike the others proactive and reactive algorithms, that try to solve the fragmentation caused by the allocation of connections of the RSA algorithm, in this case FAR RF, obtaining a high Entropy, but getting a better BP anyway, because of the constant reconfigurations. This also can explain the behaviour of the curve of FAR-RF-SDUIS, that goes up and down in the Entropy metric, because when the defragmentation is invoked, the algorithm can reconfigure all of the established connections, leaving the spectrum in a good non-fragmented state, improving the Entropy (curve goes down), but this state changes again as the RSA keeps carelessly allocating new connections, worsening the Entropy (curve goes up). It is also safe to say that, for this last case, the misalignment is a critical factor that was not considered by this metric, this is why the curve of FAR-RF-SDUIS, in low traffic, had one of the best results on Entropy, but performed poorly compared to the other ones in BP, because all of the available spectral resources in the links, that the low entropy reflects, may not be aligned to accommodate new connections, hence, the BP increases.

In the Fig. 8 and 9 the results of the Bandwidth Fragmentation Ratio metric are shown. With low traffic loads, the algorithms FA: FA-P-CF-RSA, FA-CA-RSA, and FA-MNFR-RSA, effectively obtained a better performance than the rest of the algorithms. We can see that the algorithm FA-MNFR-RSA, got one of the best BFR, but, not one of the best BP. This happens, because of the same misalignment factor mentioned earlier in the other metric. The good FR results of FA-MNFR-RSA, cannot be reflected on the BP, because the FR only considers the contiguity of the slot-blocks, not their alignment. In the Fig. 9, with high traffic loads, and in a congested network, all the algorithms follow the same trend, because, as we mentioned earlier, there is only a little room left for the defragmentation to operate efficiently.

The obtained results in the Scenario 2, for long and short holding time, can be seen in the Fig. 10 and 11. In Fig. 11 for long holding time, we can see that all the defragmentation algorithms improve their BP, compare to the results of the Fig. 10 for short holding time. This happens because the connections with a short holding time, are frequently assigned to the network, reconfigure with a defragmentation algorithm if necessary, and then terminated; constantly leaving a large amount of isolated slot-blocks in their former routes. However, when the connections stays for a longer time in optimal routes and slot-blocks, it causes less conflicts with the other connections, hence, minimizing the BP.

The results of the Scenario 3, where we analyze the performance of the algorithms with connection request of fixed, and dynamic bandwidth, can be seen in Fig. 12 and 13. In the Fig. 12 we can see that the FA algorithms that considered misalignment, got far better results than the others, because when the size of the FS is fixed, the alignment of the available slot-blocks happens easily.

For the Scenario 2 and 3, we left out the results of the Entropy and Bandwidth Fragmentation Ratio metrics, because they show the same trends as in Scenario 1.

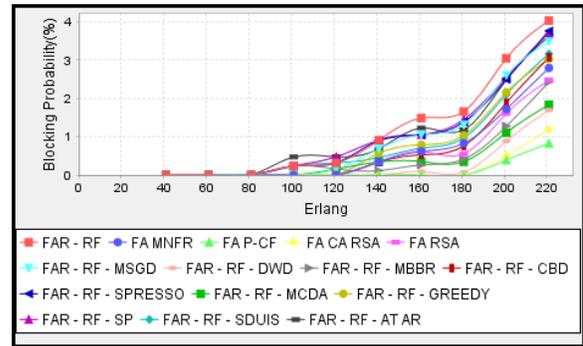


Fig. 4: Blocking Probability in Scenario 1 for Low Traffic Load

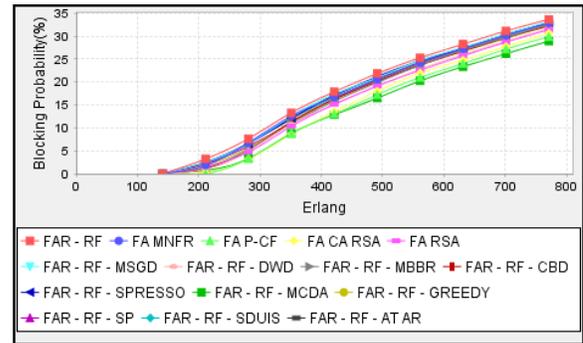


Fig. 5: Blocking Probability in Scenario 1 for High Traffic Load

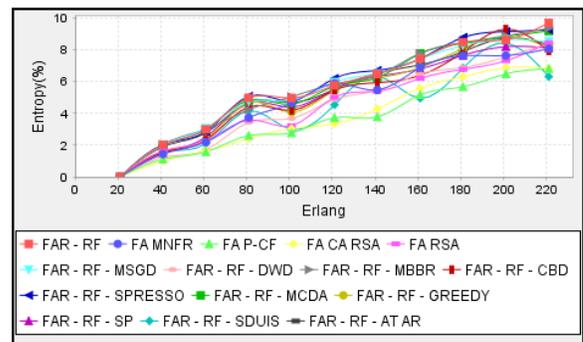


Fig. 6: Entropy in Scenario 1 for Low Traffic Load

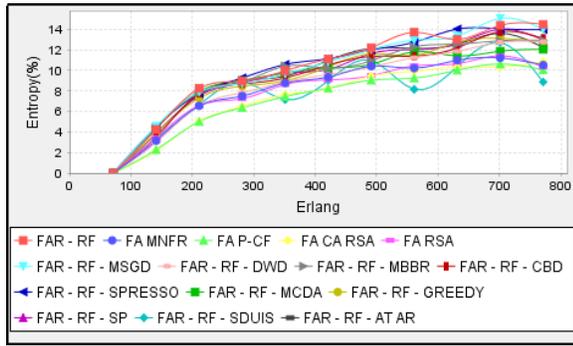


Fig. 7: Entropy in Scenario 1 for High Traffic Load

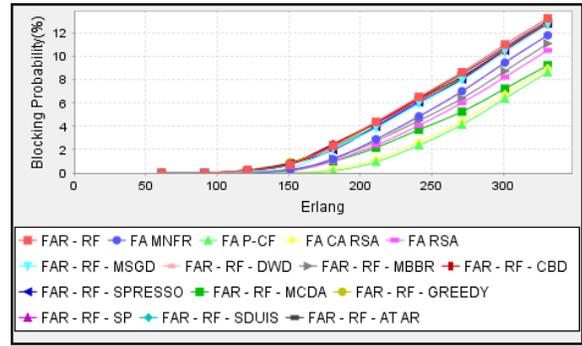


Fig. 10: Blocking Probability in Scenario 2 for short holding time

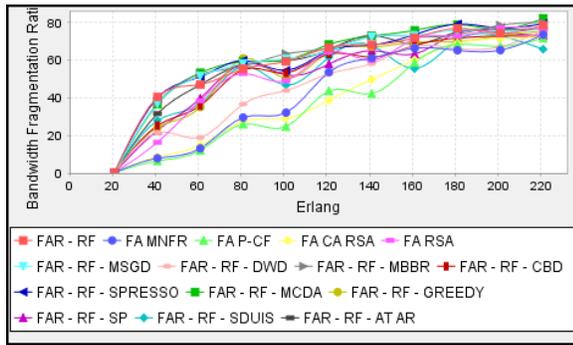


Fig. 8: Bandwidth Fragmentation Ratio in Scenario 1 for Low Traffic Load

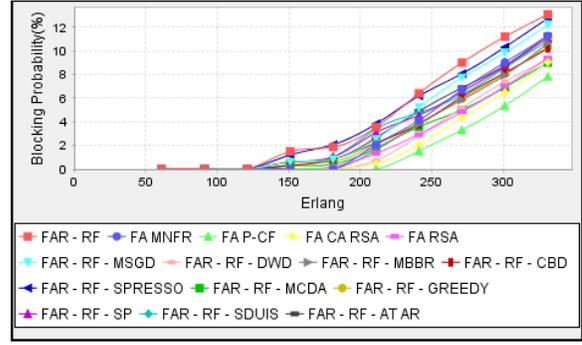


Fig. 11: Blocking Probability in Scenario 2 for long holding time

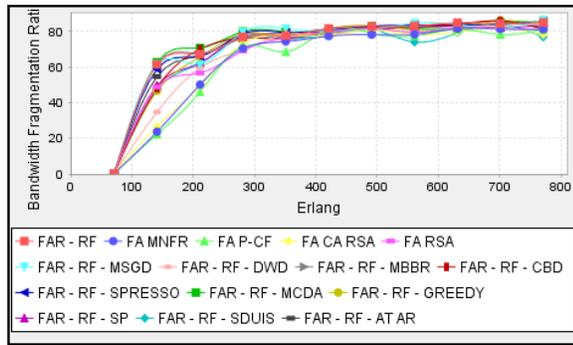


Fig. 9: Bandwidth Fragmentation Ratio in Scenario 1 for High Traffic Load

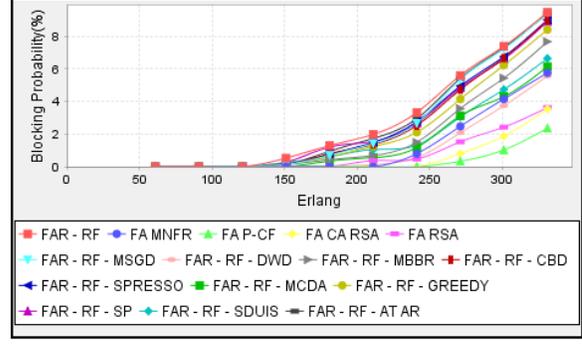


Fig. 12: Blocking Probability in the Scenario 3 for fixed FS

VI. CONCLUSIONS AND FUTURE WORKS

In this work we have presented an analysis of the Non-Hitless Defragmentation Algorithms in EON, with reactive and proactive approaches, that include rerouting and non-rerouting schemes, and compared their performance in terms of Blocking Probability, Entropy, and Bandwidth Fragmentation Ratio. The simulation results showed the following: in terms of Blocking Probability, the Fragmentation Aware RSA algorithms outperformed the other algorithms in low traffic loads, but in high traffic loads, the reactive approaches are a better

option. When the holding time of the connections is longer, the application of defragmentation is more critical, because the connections are consolidated for longer time in the spectrum; and the Fragmentation Aware RSA algorithms that consider misalignment outperformed the rest of the algorithms when the bandwidth of the connection request are fixed. Regarding the metrics of Entropy and Bandwidth Fragmentation Ratio, a better results on those metrics, not necessarily reflects in a better Blocking Probability due to the continuity constraint, that is not considered by this metrics. We will be extending this work considering the Hitless Defragmentation Algorithms, adding other topologies and different traffic scenarios.

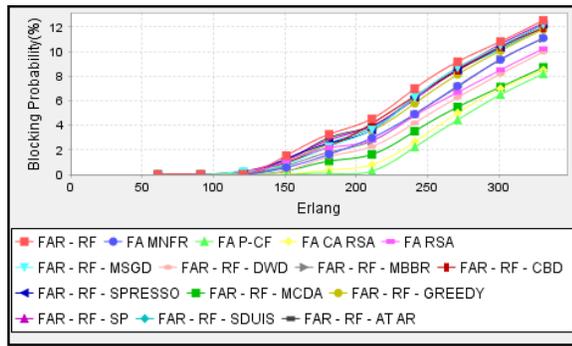


Fig. 13: Blocking Probability in the Scenario 3 for dynamic FS

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