Spectrum Allocation Policies in Fragmentation Aware and Balanced Load Routing for Elastic Optical Networks

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***Abstract*— The rigid nature of wavelength division multiplexing (WDM) routed networks leads to inefficient capacity utilization. Thus, flexible networks are a possible breakthrough for Internet technology, as long as they provide higher spectrum efficiency use. Several discrete-time simulations were carried out in Matlab in order to analyze different spectrum allocation policies (First-Fit, Exact-Fit and Random-Fit) in some routing algorithms: The Fragmentation Aware Assignment (FA), the Shortest Path with Maximum Spectrum Reuse (SPSR) and the Balanced Load Score Spectrum Assignment (BLSA). Two network topologies were used: a small 6-node subset of Cost239 and a 7-node random topology. As physical layer effects were not included as constraints, Fragmentation Aware and Balanced Load Spectrum Assignment strongly outperformed Shortest Path with Maximum Spectrum reuse, with much better results for BLSA. The separation between First-Fit and Exact-Fit curves was smaller in SPSR than in FA and BLSA. In general, Exact-Fit spectrum allocation policy presented slightly better performance than First-Fit.**

Keywords-Routing; spectrum allocation; elastic optical networks.

I. INTRODUCTION

The rigid nature of wavelength division multiplexing (WDM) routed networks leads to inefficient spectrum utilization, a problem that is expected to become much more critical with the deployment of higher capacity WDM networks. Thus, flexible networks are required to provide high spectrum efficiency use in order to achieve scalability, reduce network power consumption and decrease per unit bandwidth cost.

Optical Orthogonal Frequency-Division Multiplexing (O-OFDM) is one of the promising modulation techniques for optical networks. Optical OFDM distributes the data on several low data rate subcarriers. The spectrum of adjacent subcarriers can overlap, since they are orthogonally modulated [1], providing good spectral efficiency, flexibility and tolerance to impairments.

OFDM-based elastic optical networks achieve multiple data rate sub-wavelength or super-wavelength paths through flexible granular grooming and switching in the spectrum domain, using data-rate/bandwidth-variable transponders and bandwidth-variable optical cross-connects [2].

The data-rate/bandwidth-variable transponder provides no more than the enough subcarriers to treat sub-wavelength traffic. It is also possible to create super-wavelength paths to transport multiple-rate data traffic, by merging several OFDM channels.

Transmitted signals are routed over the optical path through bandwidth variable optical cross-connects, designed to allocate a cross-connection with the suitable spectrum to create an appropriate-sized end-to-end optical path.

The approach of the following sections is directed to routing and spectrum allocation algorithms, as long as traditional routing and wavelength assignment algorithms can no longer be directly applied to establish an elastic optical path that uses flexible spectrum width to accommodate multi-data rate services.

Section II defines the routing and spectrum allocation problem in flexible optical networks. In Section III, First-Fit, Exact-Fit and Random-Fit spectrum allocation policies are described in details. Section IV presents the results of the deployed simulations. Finally, Section V presents the conclusion and the perspectives of this work.

II. ROUTING AND SPECTRUM ALLOCATION

There is an increasing number of works searching for solutions to the elastic optical network Routing and Spectrum Allocation (RSA) problem. The RSA treats routing and spectrum allocation in order to save spectral resources, in an optimized optical network operation.

The capacity requirement of each connection request is characterized by a number of subcarrier slots, based on the capacity of the subcarriers.

Integer Linear Programming formulations are not scalable to large networks and many heuristic algorithms have been developed to treat connection requests sequentially.

The RSA problem may have an one-step approach or a two step-approach. In one-step approach, as in Modified Dijkstra's Shortest Path (MSP) and in Spectrum-Constraint Path Vector Searching (SCPVS), the algorithms define the route and the available contiguous spectrum simultaneously. On the other hand, in a two-step approach, routing and spectrum assignment are sub-problems that are solved sequentially. In the following subtopics, the Fragmentation Aware Assignment, the Shortest Path with Maximum Spectrum Reuse and the Balanced Load Score Assignment algorithms are described. After routing, spectrum allocation is performed using one of the possible existing policies.

A. Constraints

There are several restrictions to be observed in RSA problems: The traffic demands for a node-pair should be exactly added in the source node and dropped at the destination point; one sub-carrier in a fiber can only be used to serve one spectrum path; each optical path should use the same subcarriers along its entire way; overlapping spectrum paths must be separated by a number of subcarriers called guard-carriers and, finally, the employed subcarriers in a spectrum path must be consecutive in the frequency domain.

B. Shortest Path with Maximum Spectrum Reuse

For a given set of spectrum path request pairs, the sub-carrier reuse can be increased by reducing the maximum sub-carrier number. Shortest path with maximum spectrum reuse (SPSR) algorithm, proposed in [3], combines the shortest path routing with the maximum reuse spectrum allocation (MRSA) algorithm, where simultaneous spectrum path requests are first sorted according to the size of the traffic demand and larger traffic demands have higher allocation priority.

C. Balanced Load Score Spectrum Allocation (BLSA)

Proposed in [3], BLSA determines the routing through a load balancing, in order to decrease the maximum subcarrier number on a fiber. In the beginning, a k-shortest path algorithm is used to generate k paths for each source-destination pair. Then, a path is selected by estimating the load of the fibers. The maximum fiber load (MFL) of each path is taken and the better path is the one that presents the smaller MFL. Finally, after the path selection, the spectrum allocation is made through one of the possible allocation strategies (First-Fit, Exact-Fit or Random-Fit, for example). In the situation of simultaneous requests, larger traffic demands have higher allocation priority over smaller ones.

The load of a fiber (FL) can be estimated using the sum of the size of all requests, i.e., the total amount of occupied slots (SUM) in the considered link, the quantity of guard carriers (GC) and the number of optical paths (I) at that fiber, according to (1).

$$FL = SUM + GC \times (I-1) \tag{1}$$

D. Fragmentation Aware Routing (FA)

Fragmentation is not directly related to the spectrum utilization but it can be used as a decisive parameter for routing. The process of adding and ending connections in a non-uniform bandwidth assignment generates an interleaved spectrum. Obviously, spectrum fragmentation becomes a problem when free resources are broken into portions that are smaller than incoming bandwidth requests. Hence, these small non-contiguous free frequency bands reduce the spectrum efficiency gained by flexibility in the bandwidth allocation.

In the developed FA algorithm, the external fragmentation formulation, presented in [4], is used to select one of the k paths generated by the k-shortest path algorithm for each incoming source-destination connection request. Thus, a path is selected by the fragmentation estimation of each fiber along the way. The maximum fiber fragmentation (MFF) of each path must be taken and the chosen path is the one that presents the smaller MFF. After the path selection, the spectrum allocation is made through one of the possible allocation strategies. In the situation of simultaneous requests, larger traffic demands have higher allocation priority over smaller ones.

The external fragmentation of a fiber can be calculated by (2), where the largest free block (LFB) is the number of slots of the largest contiguous free space, and total free (TF) is the total amount of free slots.

$$F_{ext} = 1 - (LFB/TF) \tag{2}$$

III. SPECTRUM ASSIGNMENT POLICIES

In elastic optical networks, the assignment of spectrum slots is in different granularities to the arriving connection requests.

A first-fit assignment policy serves the request in the first available frequency band fitting the spectrum demand, a random allocation policy places incoming requests in any available block large enough to satisfy the necessary bandwidth and an exact-fit assignment, proposed in [4], searches for the exact available block in terms of the number of slots requested for the connection. If there is no block that matches perfectly, the spectrum is allocated in the first largest free block available.

IV. RESULTS

Some simulations were carried out in Matlab to compare different existing routing and spectrum assignment algorithms for elastic optical networks. The dynamic events were simulated in a 6-node subset of Cost239 and in a 7-node fiber based structure, as shown in Figures 1 and 2, respectively.

As long as the main purpose of the simulations is to compare different spectrum assignment policies in Fragmentation Aware Routing and in Balanced Load Spectrum Assignment, a distance-adaptive modulation level selection has not been configured for use. Actually, for each source-destination request, the algorithms simply select a route and try to allocate the incoming connection in one of the available sets of contiguous frequency slots, according to the chosen technique and observing all the constraints. For each source-destination pair, routes are chosen from a list created by Yen's k-shortest path algorithm.

Contiguous spectral paths were set to be separated by one guard carrier. Each type of connection is represented by one of the values in the set C = {4, 5, 6, 8, 10, 12, 14, 16}. The elements of C are the number of contiguous slots needed to satisfy bandwidth requirements. For each one of these incoming request types, it has been considered an arrival rate following a Poisson distribution.

At each time unit of the simulations, all the incoming request types were randomly associated to source-destination pairs. 400 spectral slots were defined for each fiber link. The service time of each connection follows exponential probabilities of Poisson.

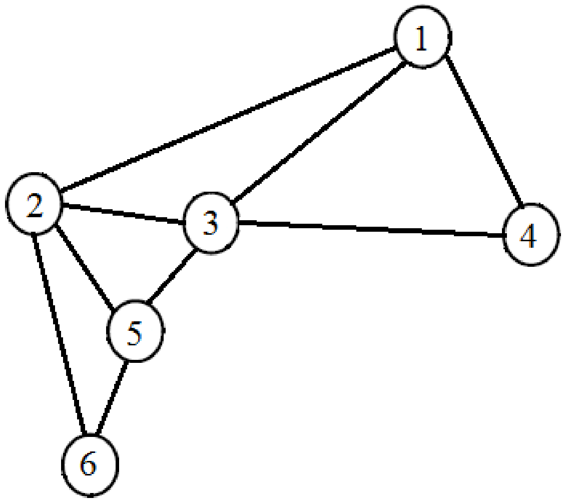

Figure 1. The 6-node subset of Cost239 network used for numerical evaluations

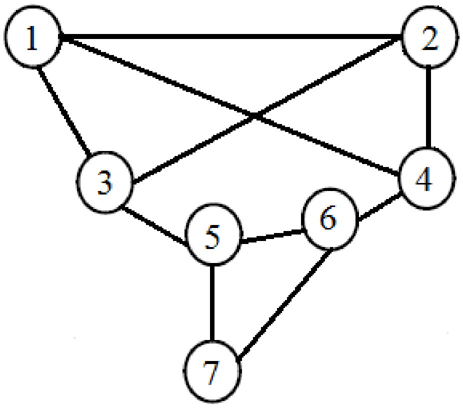

Figure 2. The 7-node random topology used for numerical evaluations

Each number associated with incoming requests load (IRL) in Tables I and II represents the blocking frequency average of five deployed simulations for the routing techniques specified in the columns. The IRL was defined as the product between the average service time, the average arrival rate and the number of connection requests. In the lines of the presented tables, this load is displayed normalized in relation to the IRL of one of the lines. Table I refers to the 6-node subset of Cost239 and Table II refers to the 7-node random topology, with First-Fit policy as spectrum allocation technique used. The last line presents the general averages of the 60 implemented simulations. Figures 3 and 4 depict the data presented in Tables I and II, respectively, in order to compare the performances of BLSA, FA and SPSR.

TABLE I. BLOCKING FREQUENCY AVERAGES FOR SPSR, BLSA AND FA IN THE 6-NODE TOPOLOGY.

Normalized IRL	*SPSR*	*BLSA*	*FA*
1	0.0751	0	0.0121
1.5	0.1214	0.0110	0.0563
2.5	0.1302	0.0155	0.0673
4	0.1501	0.0254	0.0905
General Average	*0.1192*	*0.0130*	*0.0565*

TABLE II. BLOCKING FREQUENCY AVERAGES FOR SPSR, BLSA AND FA IN THE 7-NODE TOPOLOGY.

Normalized IRL	*SPSR*	*BLSA*	*FA*
0.2	0.0413	0	0.0052
0.4	0.1731	0.0116	0.0775
1	0.1774	0.0426	0.1214
2	0.1899	0.0504	0.1331
General Average	*0.1454*	*0.0261*	*0.0843*

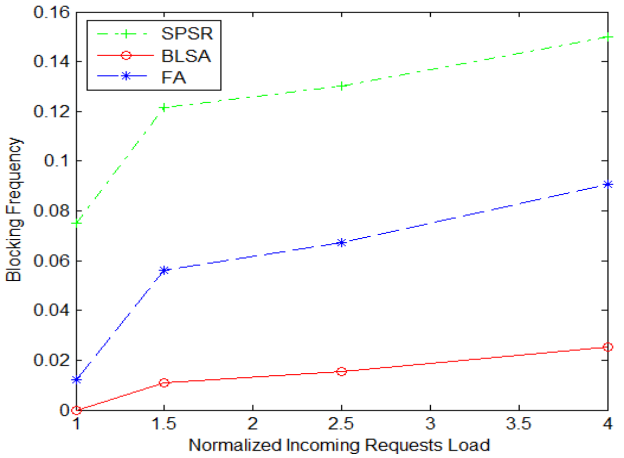

Figure 3. Blocking Frequency Comparison between SPSR, BLSA and FA for the 6-node network.

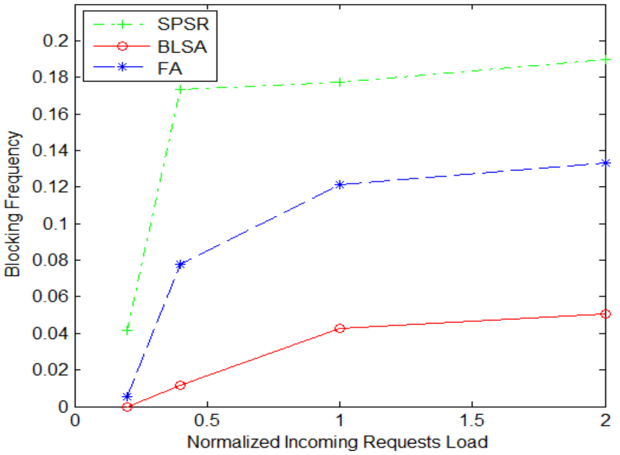

Figure 4. Blocking Frequency Comparison between SPSR, BLSA and FA for the 7-node network.

Tables III, IV, V, VI, VII and VIII present blocking frequency averages of some deployed simulations for SPSR, Balanced Load Score Spectrum Assignment and Fragmentation Aware Routing, respectively, for each topology used for numerical evaluations. Each number associated with an IRL in any of these tables is the average of 5 simulation results for the spectrum allocation policies specified in the columns, in order to compare the performances of First-Fit, Exact-Fit and Random-Fit strategies in the routing techniques proposed. The last lines are general averages.

TABLE III. BLOCKING FREQUENCY AVERAGES FOR DIFFERENT SPECTRUM ALLOCATION POLICIES IN SPSR FOR THE 6-NODE TOPOLOGY.

Normalized IRL	***SPSR***		
	First-Fit	***Exact-Fit***	***Random-Fit***
1	0.0623	0.0623	0.0609
1.6	0.1272	0.1272	0.1285
4	0.1497	0.1483	0.1510
12	0.1550	0.1550	0.1603
General Average	*0.1235*	*0.1232*	*0.1252*

TABLE IV. BLOCKING FREQUENCY AVERAGES FOR DIFFERENT SPECTRUM ALLOCATION POLICIES IN SPSR FOR THE 7-NODE TOPOLOGY.

Normalized IRL	***SPSR***		
	First-Fit	***Exact-Fit***	***Random-Fit***
0.3	0.1364	0.1395	0.1519
0.4	0.2124	0.2093	0.2078
1	0.2264	0.2264	0.2326
1.6	0.2589	0.2543	0.2543
General Average	*0.2085*	*0.2074*	*0.2116*

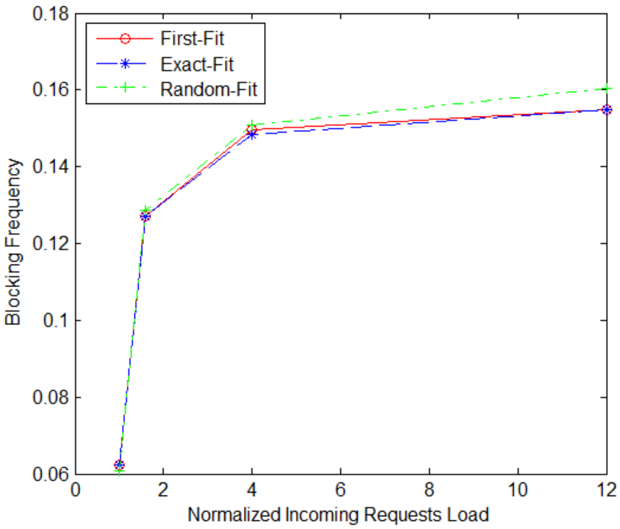

Figure 5. Blocking Frequency Performance Comparison between First-Fit, Exact-Fit and Random-Fit in SPSR for the 6-node topology.

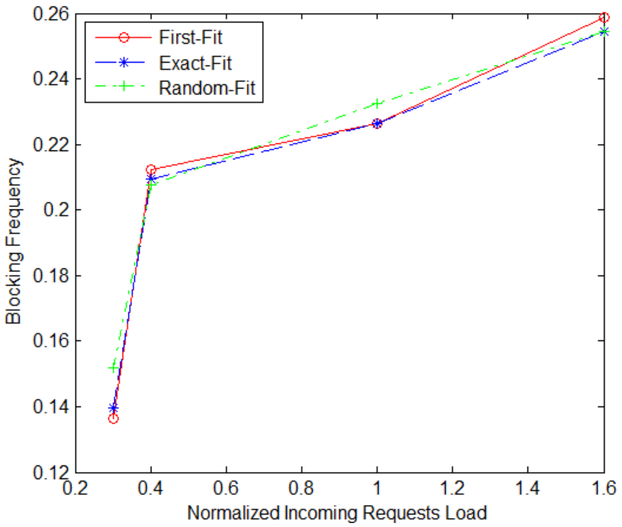

Figure 6. Blocking Frequency Performance Comparison between First-Fit, Exact-Fit and Random-Fit in SPSR for the 7-node random topology.

TABLE V. BLOCKING FREQUENCY AVERAGES FOR DIFFERENT SPECTRUM ALLOCATION POLICIES IN BLSA FOR THE 6-NODE TOPOLOGY.

Normalized IRL	***BLSA***		
	First-Fit	***Exact-Fit***	***Random-Fit***
1	*0*	*0*	*0.0053*
1.6	*0.0106*	*0.0093*	*0.0397*
4	*0.0344*	*0.0411*	*0.0689*
12	0.0517	0.0490	0.0570
General Average	*0.0242*	*0.0248*	*0.0427*

TABLE VI. BLOCKING FREQUENCY AVERAGES FOR DIFFERENT SPECTRUM ALLOCATION POLICIES IN BLSA FOR THE 7-NODE TOPOLOGY.

Normalized IRL	***BLSA***		
	First-Fit	***Exact-Fit***	***Random-Fit***
0.3	0.0109	0.0078	0.0155
0.4	0.0217	0.0171	0.0341
1	0.0372	0.0372	0.0450
1.6	0.0434	0.0419	0.0620
General Average	*0.0283*	*0.0260*	*0.0391*

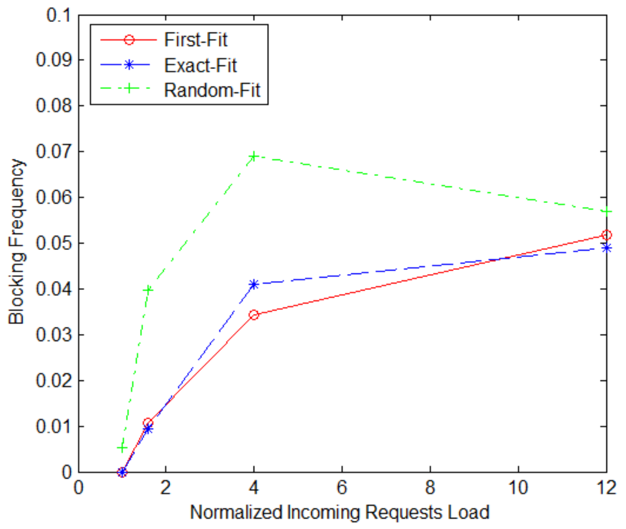

Figure 7. Blocking Frequency Performance Comparison between First-Fit, Exact-Fit and Random-Fit in BLSA for the 6-node subset of Cost239.

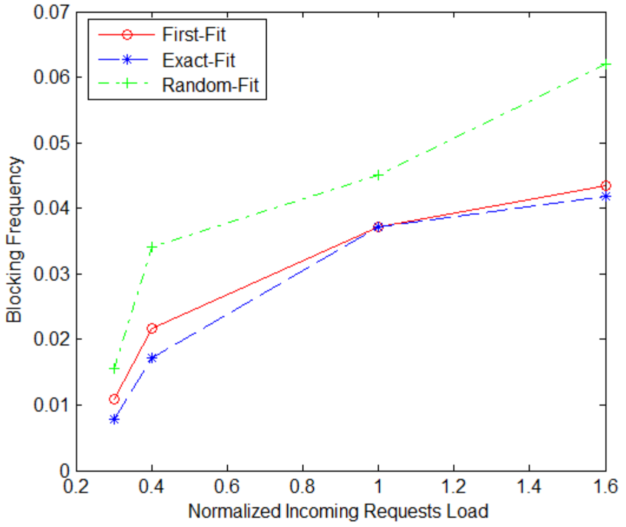

Figure 8. Blocking Frequency Performance Comparison between First-Fit, Exact-Fit and Random-Fit n BLSA for the 7-node random topology.

TABLE VII. BLOCKING FREQUENCY AVERAGES FOR DIFFERENT SPECTRUM ALLOCATION POLICIES IN FRAGMENTATION AWARE ROUTING FOR THE 6-NODE TOPOLOGY.

Normalized IRL	***FA***		
	First- Fit	***Exact-Fit***	***Random-Fit***
1	0.0159	0.0265	0.0556
1.6	0.0583	0.0623	0.1099
4	0.0954	0.0848	0.1285
12	0.1060	0.1113	0.1192
General Average	*0.0689*	*0.0712*	*0.1033*

TABLE VIII. BLOCKING FREQUENCY AVERAGES FOR DIFFERENT SPECTRUM ALLOCATION POLICIES IN FRAGMENTATION AWARE ROUTING FOR THE 7-NODE TOPOLOGY.

Normalized IRL	***FA***		
	First- Fit	***Exact-Fit***	***Random-Fit***
0.3	0	0.0465	0.0667
0.4	0.0078	0.0992	0.1256
1	0.0248	0.1442	0.1442
1.6	0.0667	0.1349	0.1643
General Average	*0.0248*	*0.1062*	*0.1252*

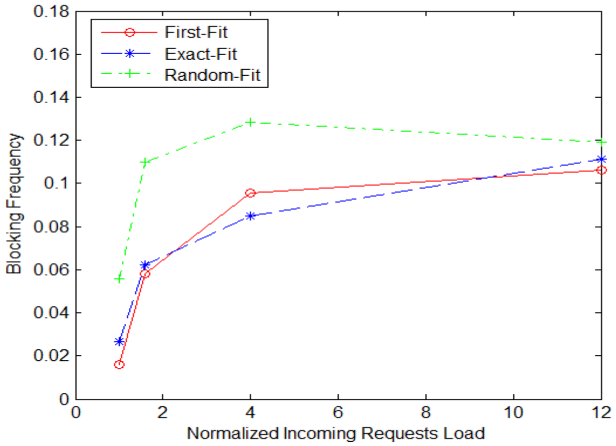

Figure 9. Blocking Frequency Performance Comparison between First-Fit, Exact-Fit and Random-Fit in FA for the 6-node subset of Cost239

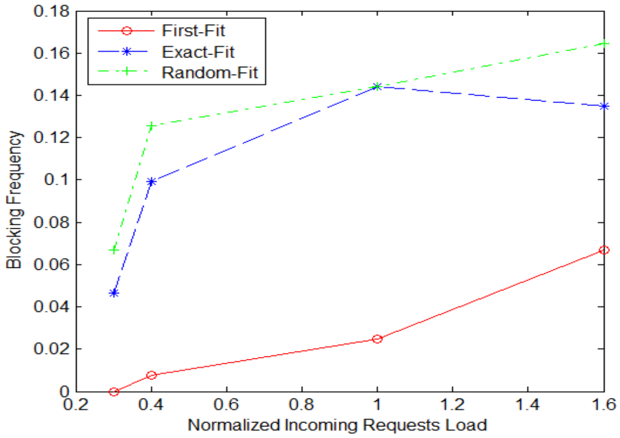

Figure 10. Blocking Frequency Performance Comparison between First-Fit, Exact-Fit and Random-Fit spectrum allocation policies in FA for the 7-node random topology.

Figures 5, 7 and 9 illustrate the data presented in Tables III, V and VII, respectively, in order to compare the performances of First-Fit, Exact-Fit and Random-Fit spectrum allocation policies in the 6-node subset of Cost239 deployments. Figures 6, 8 and 10 illustrate the data presented in Tables IV, VI and VIII, respectively, in order to compare the performances of First-Fit, Exact-Fit and Random-Fit spectrum allocation policies in the 7-node random topology proposed.

V. CONCLUSIONS

As non-linear physical layer effects were not included in the deployed network simulations, Balanced Load Score Spectrum Assignment and Fragmentation Aware Routing Techniques strongly outperformed Shortest Path Routing, with much better results for BLSA. However, it is essential the continuous searching for better formulations and strategies over the problem of fragmentation to optimize the performance of algorithms that work with it as a decisive parameter for routing. In the developed algorithms, only the concept of external fragmentation was explored.

The separation between First-Fit and Exact-Fit curves was smaller in SPSR than in BLSA and FA. In general, Exact-Fit spectrum allocation policy presented slightly better performance than First-Fit. However, as it did not happen in all the cases, a much larger number of simulations in other topologies is necessary to reach a strong conclusion on this matter.

Thus, future works might include studies on correlation between fragmentation and blocking probability, as long as other routing and spectrum allocation algorithms.

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