Routing, Core and Spectrum Assignment based on Connected Component Labelling for SDM Optical Networks

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Abstract—**This paper introduces a novel Routing, Core and Spectrum Assignment (RCSA) algorithm based on the Connected Component Labelling (CCL) algorithm. The RCSA algorithm represents the spectrum of multicore fibers as matrices and the CCL algorithm discovers with low computational complexity the available spectrum to allocate to a connection request. Spectrum fitting policies are also proposed to be jointly employed with the CCL algorithm. Results show the feasibility of utilizing image processing algorithms such as the CCL in RCSA algorithms, given that they demand low computational complexity and yet produce low blocking ratio.**

I. INTRODUCTION

In the past decade, there has been a growth of heterogeneous applications over the Internet. While some applications such as e-mail have low bandwidth requirements, others have high demands, such as IPTV [1]. The elastic (flexgrid) optical network technology can cope with such heterogeneous demands since they employ a fine-grained spectrum multiplexing, capable of allocating different bandwidths demands. These networks employ Orthogonal Frequency Division Multiplexing (OFDM), which divides the spectrum into several slots (also called subcarriers) with low data rates and overlapping orthogonal frequencies. Such multiplexing technology achieves high spectrum allocation efficiency and wastes less resources when compared to traditional Wavelength Division Multiplexing [2].

However, optical network technology is expected to reach its physical limitation in a near future with the increase in bandwidth from the Internet applications. To expand the transmission capacity of optical fibers, space division multiplexing (SDM) has been proposed [3]. Employing multicore fibers (MCF) is one of the promising choice for SDM, since it employs several independent cores in a fiber, allowing them to be treated as single core fibers (SCF) [4] [5] [6].

The Routing and Spectrum Assignment (RSA) problem in elastic optical networks consists in finding routes and available spectrum to establish a connection. Such allocation is subject to the continuity and contiguity constraints. The former imposes that the set of slots assigned by an algorithm must be the same in all links along a route to avoid costy opto-electrical conversion of the optical signal, while the latter imposes that the slots allocated must be contiguous, to achieve high spectrum efficiency. In SDM optical networks, this problem is extended to the Routing, Core and Spectrum Allocation (RCSA) problem. RCSA algorithms allocate routes and spectrum as do the RSA algorithms, but in addition they allocate one or more cores for establishment of a connection. The addition of the space dimension in multiplexing increases the complexity of spectrum assignment, since the spectrum of all cores have to be taken into consideration during the allocation.

In elastic optical networks, it is common to represent the optical spectrum using a binary vector to represent slot availability [7]. In this paper, the optical spectrum in SDM networks is represented by a matrix, with the number of cores being one of the dimensions and the number of slots in each core the other dimension. The usage of a matrix opens the possibility for the application of algorithms developed for 2D binary image processing such as Connected Component Labelling (CCL) which will be employed in the RCSA algorithm proposed in the present paper.

The CCL algorithm is a fundamental algorithm in pattern analysis of digital images. Labelling is essential in various image processing applications such as fingerprint identification, character recognition, medical image analysis, to name a few. The goal is to discover objects on an image by analysing the connectivity of the pixels of the image. There are two connectivity models: the 4-connection, which considers objects formed by pixels horizontally and vertically connected and the 8-connection, which, in addition, considers pixels along the diagonal of an image [8]. Figure 1 illustrates the output of the 4-connectivity CCL algorithm. In this figure, the background pixels have label 0 and the objects with connected pixels are labelled either 1 or 2, distinguishing the two different regions found by the algorithm.

By using the CCL algorithm, the RCSA algorithm can find spectrum with low computational complexity. The connected regions match the contiguity constraint in the spectrum dimension, allocating portions of the spectrum that have contiguous slots. The algorithm can also obtain information about all the connected regions of slots and decide in which to accommodate the connection. In general, spectrum allocation approaches in the literature do not obtain such information and make greedy decisions based the state of local spectrum.

In order to simplify the usage of the CCL algorithm in

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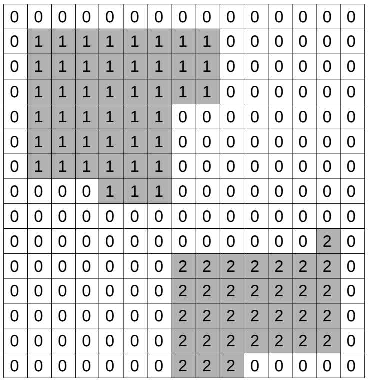

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	1	1	1	1	1	1	1	0	0	0	0	0	0
0	1	1	1	1	1	1	1	1	0	0	0	0	0	0
0	1	1	1	1	1	1	1	1	0	0	0	0	0	0
0	1	1	1	1	1	1	0	0	0	0	0	0	0	0
0	1	1	1	1	1	1	0	0	0	0	0	0	0	0
0	1	1	1	1	1	1	0	0	0	0	0	0	0	0
0	0	0	0	1	1	1	0	0	0	0	0	0	0	0
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0	0	0	0	0	0	0	2	2	2	2	2	2	2	0
0	0	0	0	0	0	0	2	2	2	2	2	2	2	0
0	0	0	0	0	0	0	2	2	2	2	2	2	2	0
0	0	0	0	0	0	0	2	2	2	2	2	2	2	0
0	0	0	0	0	0	0	2	2	2	0	0	0	0	0

Fig. 1. Labelled binary image, output of a CCL algorithm.

the RCSA algorithm, the output image, such as presented in Figure 1, is transformed in a set of regions of contiguous slots. This set consists of a collection slots and the coordinates of the slots in the matrix which represents the spectrum. Such scheme facilitate the search of regions considering their size, format and location.

This paper is organized as follows. The next section describes related work. Section III introduces the Connected Component Labelling RCSA algorithm. Section IV shows some fitting policies. Section V evaluates the use of the RCSA algorithm and the proposed fitting policies. Section VI concludes the paper.

II. RELATED WORK

In [4], an introduction to the spectrally and spatially flexible optical networks was provided, presenting the fundamental concepts, benefits and challenges. Some examples of implementation were described, proposing network components capable of transmitting data in SDM optical networks.

In [5], an overview of the possible SDM approaches, focusing on network planning was given. The paper introduced the RCSA problem (called RSMLSA by the authors) and listed the challenges due to the use of the space dimension. Network control frameworks were also presented to endorse the usage of centralized solutions based on Software Defined networks and Path Computation Elements (PCE).

In [6], an RCSA algorithm that mitigates the spectrum fragmentation was introduced. Spectrum fragmentation occurs due to the dynamic establishment and tear-down of connection of different bandwidth, leaving portions of contiguous spectrum unable to accommodate new requests. Simulation results showed that the proposed algorithm can reduce the blocking ratio when compared to approaches that do not take fragmentation into consideration. The paper also shows that the crosstalk is generated by the transmissions, and proposes a technique to monitor inband crosstalk.

In [9], an integer linear programming (ILP) formulation for the RCSA problem was introduced to minimize the maximum number of slots required by any core of a link. A heuristic is also proposed for a scalable solution. Results indicate that the heuristic approximates the optimal solution given by the ILP.

In [3], a dynamic RCSA algorithm was introduced to mitigate crosstalk. The algorithm considers the spectrum occupancy state in order to allocate a new connection, avoiding portions that would have caused unnecessary crosstalk. Results show that the approach can reduce blocking.

The CCL is a classic image processing problem, recent solutions for the problem try to diminish its computational complexity. In [10], optimization techniques are proposed to decrease the CCL problem complexity. The number of operations on pixels is decreased by representing the image as a decision tree. A streamlined union-find technique is also proposed to reduce the number of operations.

Two approaches are usually employed for the CCL algorithms: one scan and two scans. In [11], an efficient one scan approach is proposed, which performs the scanning and labelling in a single step. The algorithm support 4 and 8 connectivities. This algorithm is recommended for images containing large numbers of objects.

An efficient two scans CCL algorithm was introduced in [12], which performs the scanning and labelling in two different steps. The algorithm performs a first loop that scan connected components and attributes provisional labels, which will be replaced with the minimal correspondent label for the second scan. The algorithm needs an extra structure to store the provisional labels, but considering that there are no memory constraints, the two scans approach outperforms the one scan approach.

This paper presents a novel RCSA algorithm using the CCL algorithm for efficient allocation of available spectrum. It is of our best knowledge that there is no other work that uses image processing algorithms in the solution for the RCSA problem. The two scan approach is used in this paper for the RCSA algorithm since it performs better when compared to the one scan approach.

III. CONNECTED COMPONENT LABELLING RCSA

The RCSA algorithm was designed to operate in networks with dynamic arrival of requests for the establishment of lightpaths. It is assumed that it is implemented in ideal Path Computation Elements and that information about the status of spectrum availability is stored in PCE databases.

Since the complexity of routing algorithms for optical networks increases with the addition of the spatial dimension of multiplexing, therefore, new algorithms need to try to reduce this computational complexity. The proposed algorithm aims to keep the computational complexity low by representing the optical spectrum as a binary matrix of slots. Such representation is the same as used in binary images, and therefore, it is possible to apply developed methods in image processing to reduce the complexity of the task of finding available spectrum.

In the proposed algorithm, the optical network is represented by a graph, in which the vertices represent SDM Optical Cross Connectors (OXC), and the edges represent multi-core fibers connecting two vertices. Each edge has an associated matrix that represent its optical spectrum. Free slots of a link are represented by the value 0 in the matrix element and the 1 value is used otherwise.

A K Shortest Paths (KSP) algorithm [13] is employed to calculate routes. The spectrum of the candidate paths are then analysed to accommodate bandwidth requests.

The connected component labelling is used to efficiently discover the state of the spectrum by labelling regions of contiguous slots in the spectrum matrices, which will be used as input to the decision of which portion of the spectrum to allocate for a specific request. The choice of an available region is done by the fitting policy. Three fitting policies will be proposed in the following section.

The algorithm consists in three steps:

1) The candidate paths are calculated with the KSP algorithm;
2) To guarantee the spectrum continuity, it is needed to discover which slots are available in all links along each path. This is done by calculating a matrix that stores the result of a binary AND operation between the spectra of the path.
3) The CCL is calculated resulting in the available contiguous regions of slots, and in case there is available spectrum, a fitting policy is used to decide in which region the connection is established.

The following notation will be used to describe the algorithm:

s: source node;

d: destination node;

b: bandwidth demand in slots;

$r(s,d,b)$: request from the node s to the node d with bandwidth demand b;

$G = (V, E, S)$: network graph composed by a set of nodes V, a set of edges E and a set of matrices S representing the optical spectrum availability in the links, which are associated with the edges of the graph;

$E = \{e_{u,v}\}$: set of edges $e_{u,v}$ connecting u and v in G;

$S = \{s_{u,v}\}$: set of matrices $s_{u,v}$ representing the spectrum of the link between u and v in G;

$P = \{p_i\}$: set of paths, used to store the result of the KSP algorithm;

$L_i = \{l_{i,j}\}$: set of regions of the spectrum, output of the connected component labelling algorithm, in which each $l_{i,j}$ is a set of slots;

m_i: auxiliary matrix that stores the contiguous slots of the path i;

$H = \{h_{j,k}\}$: set of slots allocated by the fitting function.

Algorithm 1 shows the CCL-RCSA algorithm. In Line 1, the candidate paths are calculated using the KSP algorithm, and the results are stored in a set of paths P. In Line 2, for each link of the path p_i, the spectra are summed, using the binary operation and the result is stored in m_i. This operation guarantees the spectrum continuity of the connection since the free slots of m_i are free in all links along the path. In Line 3, the CCL algorithm runs for each potential path and the sets of regions available for each path i is stored in L_i. In Line 4, if there is no set of slots with size larger than the demand d, i.e. that there is no set of contiguous slots able to accommodate the demand d, the request is blocked. Otherwise, in Line 7, a region from the list given by the CCL is chosen by the fitting policy to accommodate the bandwidth demand. The allocated slots are set as occupied in Line 8 in the spectrum matrices.

Algorithm 1 CCL-RCSA

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1: $P = KShortestPaths(G, s, d)$
2: $\forall j, k \mid \exists e_{j,k} \in p_i \ m_i = m_i$ and $s_{j,k}$
3: $\forall i L_i = ConnectedComponentLabelling(m_i)$
4: if $\forall i, j |l_{i,j}| < d$ then
5:     $block(r(s, d, b))$
6: else
7:     $H = fit(r(s, d, b), p_i, L_i)$
8:     $\forall h_{j,k} \ s_{j,k} = 1$
9: end if
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The computational complexity of the algorithm depends on the complexity of the CCL algorithm used [10] [14], which is $O(p)$, where p is the number of pixels in the image. This can be translated to the number of slots in all cores of the network, or $c \times s$, where c is the number of cores and s the number of slots in each core. The CCL algorithm runs k times in the RCSA algorithm, resulting in a complexity of $O(kcs)$. The values of c and s can be considered as constants for a given topology, and k is a parameter of the algorithm that can also be fixed. In a static network scenario, the algorithm will always perform the same number of operations with a fixed k, therefore, the complexity is $O(1)$.

The usage of the CCL algorithm opens the possibility to employ diverse policies to decide in which portion of the spectrum the requests should be allocated. This decision is made using fitting policies, described in the next section.

IV. FITTING POLICIES

Three fitting policies are introduced in the section: First-Fit, Best-Fit and Random-Fit. All the fitting policies proposed favors the shortest path, and try to allocate the connections considering the number of hops of the paths computed by the KSP algorithm.

The First-fit (FF) is a greedy policy that tries to allocate the request in the first possible region and in its first possible set of slots. This policy is the simplest proposed in this paper, its goal is to quickly allocate a connection regardless of its position on spectrum, which can decrease the number of operations but can lead to problems such as spectrum fragmentation.

The Best-fit (BF) policy uses the smallest free portions of the spectrum, in which it would be hard to allocate further connections on, thus, preventing spectrum fragmentation. The approach allocates the bandwidth request in a region which is the smallest one, greater than the bandwidth demand. This policy increases the number of operations compared with the FF policy, trying to efficiently fit the demand in the free portions of the spectrum.

The Random-fit (RF) policy allocates the connection on a random region that satisfies the traffic demand and then chooses a random list of contiguous slots in the region. This policy takes advantage of the equal probability of allocating portions of the spectrum to better distribute the connections, avoiding possible crosstalk.

V. NUMERICAL EVALUATION

To assess the performance of the proposed algorithm, simulation experiments were employed and the three fitting policies were compared. The parameter $k = 3$ was used in the KSP algorithm since no significant gain were observed with higher values. The FlexGridSim [15] simulator was employed in the simulations. Each replication simulated 100,000 requests as input. Confidence intervals with 95% confidence level were generated. The NSF (Figure 3) and the USA (Figure 2) topologies were used in the simulations. The NSF topology has 16 nodes and 25 links whereas the USA topology has 24 nodes and 43 links. The links were composed by MCFs with 7 core and each core was divided in 264 slots of 12,5GHz [16]. Connections were dynamically generated by randomly selecting source and destination pairs. The traffic load is given by the utilization of the bottleneck link, which presents the current higher amount of optical lighpaths assigned [3].

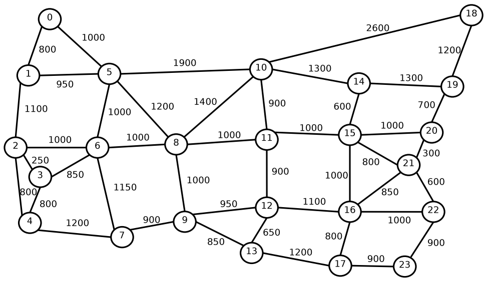

Fig. 2. The USA topology.

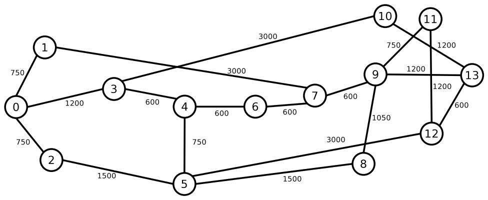

Fig. 3. The NSF topology.

Figure 4 shows the bandwidth blocking ratio (BBR) as a function of the load for the USA topology. The algorithm produces overall low BBR values, with all values under 0.01. Under low loads, the FF and BF policies block less connections when compared to the RF policy, being the differences in BBR of up to two orders of magnitude. As the load increases the difference of BBR decreases and the FF and RF policies produce similar BBR under loads of 0.7. The same occurs to BF and RF under loads of 0.8. Under loads close to 1.0, the best performing policy is the RF, producing BBR one order of magnitude lower than those given by the two other policies. As expected the BF policy performs better than the greedy FF under all loads, since the naive approach of FF often leads to non optimal solutions. Although the RF policy achieves lower blocking ratios under high loads, its random nature leads to a higher blocking ratio under low loads, which discourages its usage.

The high variability of BBR under low loads for the USA topology happens due to its high number of alternative routes and the greedy approach of the BF and FF policies.

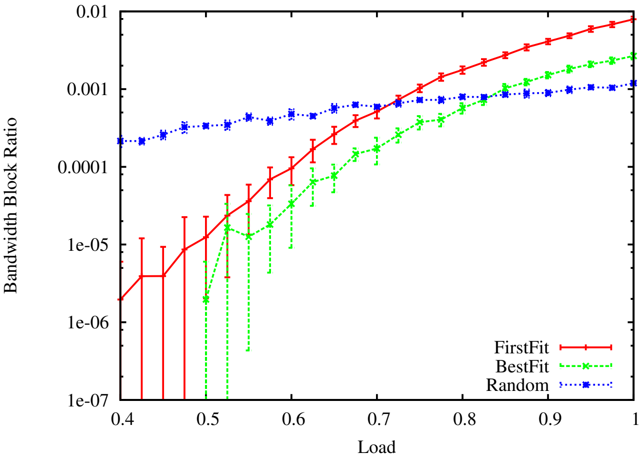

Fig. 4. Bandwidth Blocking Ratio as a function of the load for the USA topology.

Figure 5 shows the average Crosstalk per Slot (CpS) for the USA topology. The crosstalk per slot is the average ratio between slots being affected by crosstalk and the total slots used in a link. The RF allocations are less affected by crosstalk due to its ability to spread the connections over the optical spectrum, obtaining CpS as low as 0.3, compared to values between 0.45 and 0.61 given by the BF and FF policies, respectively.

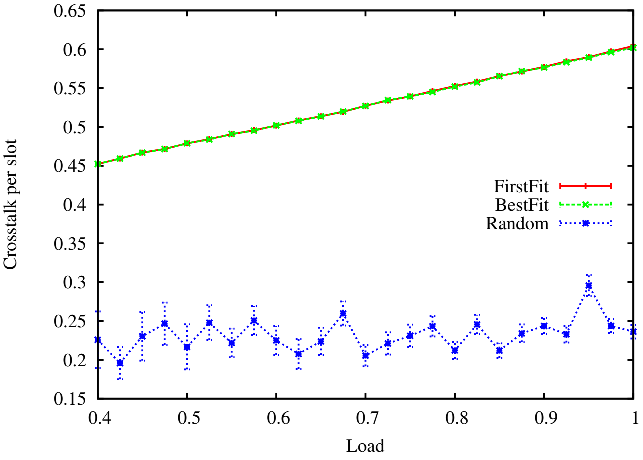

Fig. 5. Crosstalk per Slot as a function of the load for the USA topology.

Figure 6 shows the Jain Fairness Index (JFI) for the pair of source and destination nodes for the USA topology. The values of JFI are low for all algorithms, which can be explained by the trend of blocking connections that use the bottleneck links and, as a consequence, several pairs of nodes experience no blocking, decreasing the JFI value. When comparing the proposed policies, the RF policy achieves the highest JFI values, which is double the values given by FF under all loads. This is achieved because of the randomness of RF policy, leading to distributed blocking among the nodes.

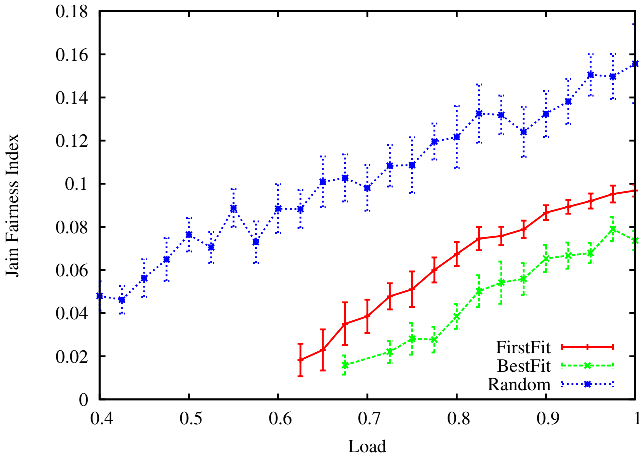

Fig. 6. Jain Fairness Index as a function of the load for the USA topology.

Figure 7 shows the average number of hops for the established lightpaths for the USA topology. All the algorithms present similar average number of hops in their requests, varying 0.06 and with overlapped confidence intervals. The low variability is due to the usage of the KSP algorithm which calculates the paths based on the number of hops.

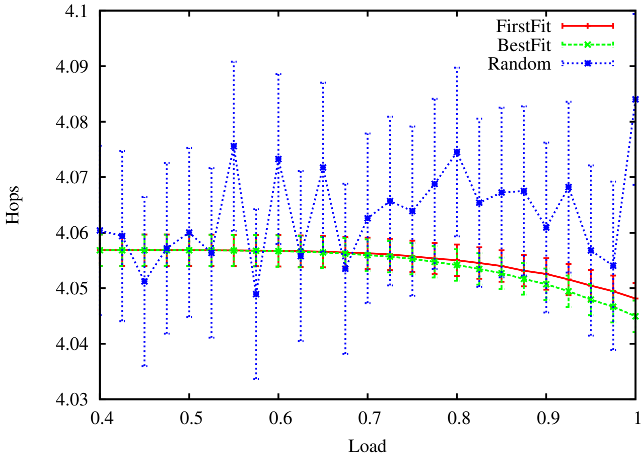

Fig. 7. Number of average hops of the lighpaths for the USA topology.

Figure 8 shows the BBR as a function of the load for the NSF topology. Results were similar to those of the USA topology. Under low loads the BF policy produces the lowest BBR, and the RF produces relatively high BBR, almost two orders of magnitude higher than those produced by FF and BF. For this topology, the greedy approach of the FF policy and the lower number of alternative routes lead to the production of BBR one order of magnitude higher than that produced by BF. The RF policy starts to produce less blocking than does BF under loads higher than 0.7; the difference is at most 47%. Since the NSF topology has less alternative paths, the variability of BBR is lower when compared to that when the USA topology is used.

Figure 9 shows the average Crosstalk per Slot for the NSF topology. Results are similar to those for the USA topology. The reduced number of alternative paths increases the difference of CpS between RF and the two others algorithms. While RF does not produce values higher than 0.3, BF and FF produce values between 0.58 and 0.82

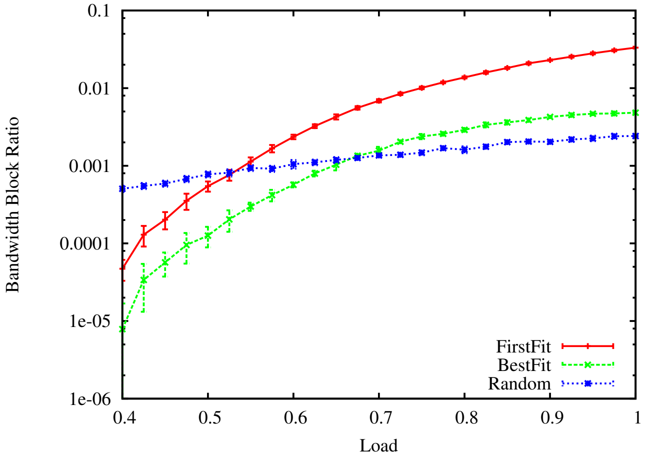

Fig. 8. Bandwidth Blocking Ratio as a function of the load for the NSF topology.

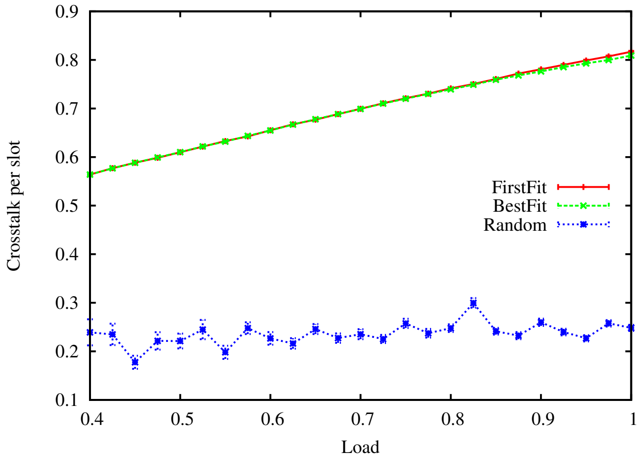

Fig. 9. Crosstalk per Slot as a function of the load for the NSF topology.

Figure 10 shows the Jain Fairness Index (JFI) for the blocking of pair of source and destination nodes for the NSF topology. The overall JFI produced by the algorithm is higher for this topology when compared to those for the USA topology since there is a lower number of alternative paths, leading to a lower number of pairs of nodes with zero blocking, leading to a more uniform distribution of blocking among the source destination pairs. As in the USA topology, the RF policy achieves the highest JFI value, being 0.4 under loads of 1.0, which is double of that produced by the two other policies.

Figure 11 shows the average number of hops in the established lightpaths for the NSF topology. The difference in the average number hops of the RF policy and those of the other two policies is clear. This illustrates the benefit of the greedy approach of the FF and BF policies, which leads to lower JFI values as well as lower blocking ratios under high loads.

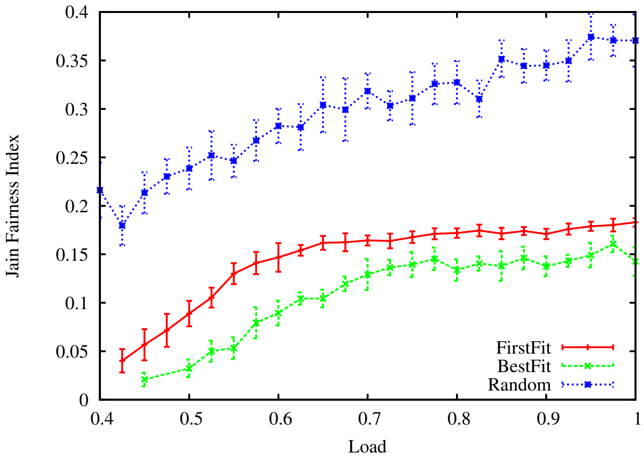

Fig. 10. Jain Fairness Index as a function of the load for the NSF topology.

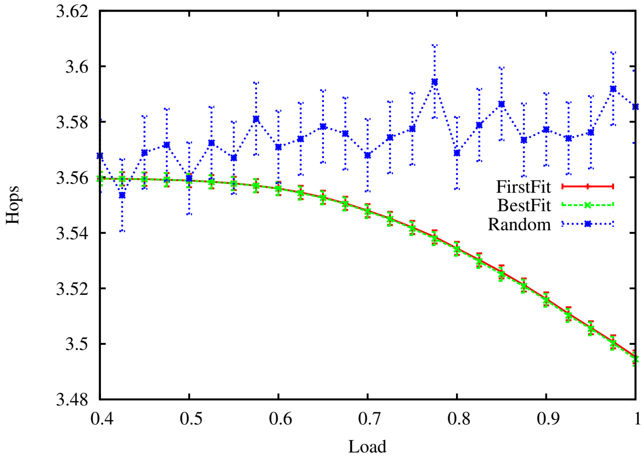

Fig. 11. Number of average hops of the lighpaths for the NSF topology.

VI. CONCLUSION

This paper introduced the CCL-RCSA algorithm which uses a Connected Component Labelling algorithm to discover with low computational complexity contiguous regions of spectrum for the establishment of connection in SDM optical networks. Three spectrum fitting policies were evaluated. Results showed that CCL algorithms can be used for finding available spectrum.

The Best-Fit policy is recommended for scenarios with lower loads, since it produces lower blocking ratios and at this load the crosstalk is lower. As for scenarios with higher loads the Random-Fit policy is recommended, as it can keep lower crosstalk and block less connections.

This paper proposed policies for spectrum fitting. We are currently working on new policies that take into consideration several network parameters. Other image processing algorithms can be also applied for the RCSA problem, and further investigation of the performance of these algorithms is needed.

VII. ACKNOWLEDGEMENTS

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