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Fragmentation Aware Routing and Spectrum Assignment Algorithm

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Abstract

In flex-grid (elastic) networks, the spectrum can be allocated at a much finer granularity than it can be allocated in WDM networks. However, the dynamic establishment and tear down of lightpaths yields to the fragmentation of the spectrum with consequent increase in blocking of requests for connection establishment. Therefore, it is of paramount importance that allocation decisions try to mitigate the fragmentation problem. In line with that, this paper introduces the Multigraph Shortest Path Algorithm for novel Routing and Spectrum Allocation (RSA) in elastic networks. Results indicate that the joint use of the new algorithm with proposed cost functions can produce bandwidth blocking ratio four orders of magnitude lower than existing RSA algorithms.

1 Introduction

One of the main characteristics of the Internet architecture is to impose no constraint on the application layer which allows the fast emergence of new applications. These applications have heterogeneous bandwidth demands. While some applications such as e-mail has low bandwidth requirements, others such as IPTV and grid applications can demand bandwidth of the order of Gbits per second [1]. Such diversity of bandwidth demands calls for a rate-flexible transport network.

The Wavelength Division Multiplexing (WDM) technique brought great capacity to the Internet link layer by allowing the multiplexing of several wavelengths in a single fiber. Traditional WDM employs a fixed-size frequency allocation per wavelength with a guard-band frequency separation between two wavelengths. In WDM, the fixed capacity of a wavelength accommodates demands of different sizes. This leads to underutilization of the spectrum since demands rarely match the exact capacity of a wavelength. Subwavelength demands are usually groomed to decrease the capacity wastage. On the other hand, suprawavelength demands require inverse multiplexing and the allocation of multiple independent WDM wavelength with wasteful allocation. Moreover, the necessary guard band between wavelengths contributes to spectrum underutilization. Although multi-rate WDM introduces

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some flexibility in resource allocation, its coarse allocation granularity can only ameliorate the problem in a limited way.

Such rigidness has recently led to the emergence of spectrum-sliced elastic optical path networking. In this technology, (Optical) Orthogonal Frequency Division Multiplexing (OFDM) is employed. OFDM is a multi-carrier transmission technology that slits high data rate channels into a number of orthogonal channels, called subcarriers, each with (subwavelength) low data rates. In the flexible grid of elastic networks, subwavelength demands are directly supported in the optical domain and superwavelength demands are granted by the aggregation of several carriers in a super-channel mantaining orthogonality among channels to save spectrum.

Similar to the routing and wavelength assignment problem (RWA) in fixed-grid WDM networks, solutions for the routing and spectrum assignment problem (RSA) in elastic optical networks are needed to efficiently accommodate traffic demands. Besides the spectrum continuity constraint that imposes the allocation of the same spectrum in each fiber along the route of a lightpath, in an RSA formulation, slots (carrier) must be contiguously allocated in the spectrum (the spectrum contiguity constraint).

However, the dynamic establishment and tear-down of channels leads to the segmentation of the available spectrum into small noncontiguous bands which is called the fragmentation problem. Fragmentation implies in low efficient use of the spectrum and increases the blocking probability of requests for connection establishment due to unavailability of contiguous bands to accommodate new requests. Therefore, it is of paramount importance that routing and spectrum assignment should be carried out in a way to minimize such problem. Indeed, the cost function employed to decide which route and part of the spectrum to allocate is one of the main aspect that leads to fragmentation of the spectrum In line with that, this paper introduces the Multigraph Shortest Path algorithm, a novel algorithm for the RSA problem that allows the use of traditional shortest path algorithms and it proposes different cost functions to reduce fragmentation. It is shown that the use of Multigraph Shortest Path produces bandwidth blocking ratio that can be four order of magnitude lower than those given by existing RSA algorithms.

This paper is organized as follow. The next section describes related work. Section III introduces the Multigraph Shortest Path algorithm and new cost functions. Section IV evaluates the performance of the MSP algorithm and compare it to existing ones. Section V concludes the paper.

2 Related Work

Solutions to the RSA problem have been proposed for both static and dynamic scenario. In, [2], [3], [4] Integer Linear Programming formulations were proposed for the static version when all request are known in advance. However, these solutions have high computational cost. For the dynamic scenario, heuristics have been proposed [5]. The Modified Shortest Path (MSP) algorithm employs a Dijkstra like algorithm which at each iteraction computes the cost of path going through a neighboring node if the nodes are connected by contiguous slots enough to satisfy the requested bandwidth. The Spectrum-Constraint Path Vector

Searching (SCPVS) algorithm builds a tree to represent the potential paths. At every step, it adds a leave to the tree and computes the cost of this addition. Information about the paths is stored in an auxiliary data structure. Since it searches for all possible paths, it produces blocking probability lower than the ones given by the MSP.

The survey in [6] discusses several algorithms for the RSA problem as well as the fragmentation problem. In [7], traffic aggregation is proposed to diminish fragmentation in WDM flex-grid networks. In [8], a procedure for matching spectrum fragmentation and bandwidth demands is introduced. The work in [9] introduces procedures to avoid and to ameliorate fragmentation when it occurs. A procedure was introduced in [10] to reallocate the connections according to existing fragmentation and pattern of use of slots. However, these last two works implies in interrupting the connection for reallocation of the spectrum.

The present work differs from the existing ones by the representation of the spectrum occupancy and cost functions adopted which translates the potentiality to use spectrum fragments by incoming requests.

3 The Multigraph Shortest Path Algorithm

The Routing and Spectrum Assignment algorithms proposed in this section was designed to operate in networks with dynamic arrival of requests for the establishment of lightpaths. It is assumed that the RSA algorithm is implemented in ideal Path Computation Elements (PCE) and that information about the status of spectrum availability is stored in the PCEs databases. The algorithm does not consider advanced modulation format in OFDM-based transmission as well as filter guard band and physical constrains. All these aspects were not included in the formulation. The proposed algorithm is, therefore, a first step towards the elaboration of algorithms that will include other aspects for coping with fragmentation.

It has been proved that the Routing and Spectrum Allocation problem is an NP-hard problem and heuristics are needed to solve the problem. The proposed algorithm models the spectrum availability in the network as labeled multigraph. A multigraph is a graph which is permitted to have multiple edges (also called "parallel edges"), that is, edges that have the same end vertice. In this auxiliary graph, vertices represent OXCs and edges the slots in the link connecting OXCs. All vertices are connected by N edges which is the number of slots in the spectrum of each network link. The label on an edge represent the slot availability. An ∞ value means that the slot is already allocated whereas the value 1 means that the slot is available for allocation. These values were defined to facilitate the employment of traditional shortest path algorithms.

The multigraph is transformed in $N - b + 1$ graphs where b is the bandwidth demand in slot of the requested channel. These graphs are generated by fixing an edge of the multigraph and considering the b consecutive edges to the fixed edge. This set of b edges of the multigraph are mapped onto a single edge of the generated graph. Its cost is given by applying a specific cost function that considers the b edges. Figure 1 illustrates the multigraph representing the spectrum and one of the generated graph. For each of the generated graphs, a shortest path algorithm is executed and the chosen path is the one that has the lowest cost among all shortest paths found.

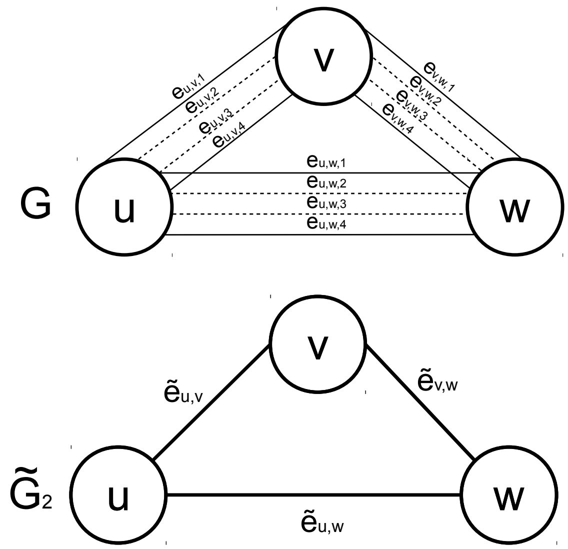


Figure 1: Multigraph representaion of the spectrum

The following notation will be used to describe the algorithm:

s: source node;

d: destination node;

b: bandwidth demand in slots, $b = 1 \ldots N$;

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

N: number of slots between two nodes;

$G = (V, E, C)$: labeled multigraph composed by a set of nodes V, a set of edges E and a set o edge costs C, $|E| = N \cdot |V|$. The edges connecting two vertices of G represent the N slots in the link connecting two network nodes;

$E = \{e_{u,v,n}\}$: the n^{th} edges connecting u and v;

$c(e_{u,v,n})$: cost of the edge $e_{u,v,n}$; $c(e_{u,v,n}) = 1$ if the n^{th} slot in the link connecting OXC u and v is free and $c(e_{u,v,n}) = \infty$ if the slot is already allocated;

$C = \{c(e_{u,v,n})\}$:set of edge costs

$\widetilde{G}_n = (\widetilde{V}, \widetilde{E}, \widetilde{C})$: the n^{th} labeled graph such that $\widetilde{E}$ is the set of edges connecting $\{\widetilde{u}, \widetilde{v}\} \in \widetilde{V}$ and $\widetilde{C}$ is the set of costs associated to $\widetilde{E}$;

$\widetilde{V} = V$: set of nodes;

$\widetilde{e}_{u,v} \in \widetilde{E}$: edge connecting $\widetilde{u}$ and $\widetilde{v}$; $\widetilde{e}_{\widetilde{u},\widetilde{v}} = \{e_{u,v,n}\} \in E$ is a chain such that $e_{u,v,n}$ is the least ordered edge, $e_{u,v,n+b}$ is the greatest ordered edge and $|\widetilde{e}_{u,v}| = b$;

$\widetilde{c}_n(\widetilde{e}_{\widetilde{u},\widetilde{v}})$: cost of the edge $\widetilde{e}_{\widetilde{u},\widetilde{v}}$;

$\widetilde{C}_n = \{\widetilde{c}_n(\widetilde{e}_{\widetilde{u},\widetilde{v}})\}$: set of edge costs;

P_n: chain of $\widetilde{G}_n$ such that the source node s is the least ordered node and d is the greatest ordered node;

$C(\widetilde{P}_n)$: $\sum_{\widetilde{e}_{\widetilde{u},\widetilde{v}} \in \{\widetilde{P}_n\}} \widetilde{e}_{\widetilde{u},\widetilde{v}}$: the cost of the path $\widetilde{P}_n$ is the sum of the cost of all the edges in the chain;

$C_{s,d}$ = cost of the shortest path between s and d;

For a demand of b slots, $N-b+1$ graphs of type $\widetilde{G}_n$ will be generated, each edge of the $\widetilde{G}_n$ graph correspond to the mapping of b edges of G starting on the nth edge of G. Since the same ordered edges connecting any two nodes in G are mapped onto edges of $\widetilde{G}_n$, the spectrum continuity is assured.

Algorithm 1 Multigraph Shortest Path

1: $\forall n = 1...N{-}b$
2: $\quad (C(P_n), P_n) = SortestPath(\widetilde{G}_n, r(s,d,b))$
3: $C_{s,d} = C(P_n) \mid \forall i \; C(P_n) \leq C(P_i)$
4: **if** $C_{s,d} = \infty$ **then**
5: $\quad$ *block* $r(s,d,b)$
6: **else**
7: $\quad$ *establish* $r(s,d,b)$ *as* $\widetilde{P}_n$
8: $\quad C(e_{u,v,i}) = \infty \quad \forall \{u,v\} \in \widetilde{P}_i \quad n = n...i{+}b-1$
9: **end if**

Algorithm 1 details the Multigraph Shortest Path Algorithm. In this algorithm, Line 1 establishes all the set of edges that will be mapped onto $\widetilde{G}_n$ edges. Line 2 solves a shortest path algorithm for the graph $\widetilde{G}_n$ and provides the path and its cost. If the cost of the shortest path is ∞, it was not possible to find a path under the contiguity constraint for the demand b with allocation starting with the nth slot. Line 3 selects the path among the $N-b+1$ shortest paths that has the lowest cost. In case the cost of all shortest path is ∞ (Line 4), there is no path in the network that satisfies the request of b slots under the contiguity constraint. Therefore, the request has to be blocked (Line 5). Otherwise, the least cost shortest path is chosen (Line 7) and the corresponding edges in the multigraph G have their cost changed to ∞ (Line 8) meaning that the slots were allocated to the newly established lightpath.

Since the Multigraph Shortest Path Algorithm executes a shortest path algorithm $N-b$ times and considering the use of the Djkstra Shortest Path algorithm, the computational complexity of the proposed algorithm is $N \cdot (|V| + |E|) \cdot \log(|V|)$.

4 Cost Functions

The allocation and tear down of lightpaths in elastic networks leads to the fragmentation of the spectrum. In such situation, it is possible that there is a sufficient number of available non-contiguous slots to accommodate a bandwidth demand but there is not a sufficient number of contiguous slots to accommodate the demand. Actually, the selection of slots to allocate a demand greatly impacts the spectrum fragmentation. Indeed, the selection is determined by the cost function used to find a path from source to destination. Therefore, defining cost functions to minimize the spectrum fragmentation is a major issue to decrease the blocking of incoming requests for lightpath establishment. This section introduces two cost functions to the RSA problem.

Let us define the number of slots contiguously available in the link between nodes u and v as:

$$m_{u,v,i} = \begin{cases} j-i \quad if \ i \neq n \forall k \ c(e_{u,v,k}) = 1 \\ \quad k{=}i\dots j; j{=}i{+}1 \dots i{+}b{-}1 \quad and \quad c(e_{u,v,i}) = \infty \\ j-n \quad if \ \forall k \ c(e_{u,v,k}) = 1 \\ \quad k{=}n\dots j, j{=}n{+}1 \dots n{+}b{-}1 \\ 0 \quad otherwise \end{cases} \tag{1}$$

The next two cost functions consider the sequences of contiguously available slots in a link and propose different ways to use this information to avoid fragmentation.

4.1 Degree of Fragmentation

The Degree of Fragmentation function compares the maximum number of contiguously available slots to the number of available slots in the spectrum. This function assigns decreasing costs to large number of contiguously available slots and the cost is proportional to the total number of available slots. The Degree of Fragmentation cost function is given by:

$$\widetilde{c}_n(\widetilde{e}_{\widetilde{u},\widetilde{v}}) = \frac{F_{u,v,n} - M_{u,v,n}}{F_{u,v,n}} \tag{2}$$

where:

$F_{u,v,n}$: is the number of slots available in the spectrum of the link connecting nodes u and v; $M_{u,v,n}$ is the maximum number of contiguously available slot in the spectrum of the link connecting nodes u and v, which are given by:

$$F_{u,v,n} = \sum_{i=n}^{n+b-1} f_{u,v,i} \tag{3}$$

$$f_{u,v,i} = \begin{cases} c(e_{u,v,i}) & if \ c(e_{u,v,i}) = 1 \\ 0 & if \ c(e_{u,v,i}) = \infty \end{cases} \tag{4}$$

$$M_{u,v,n} = m_{u,v,n} \mid \forall j \ m_{u,v,j} \leq m_{u,v,i} \tag{5}$$

4.2 Acceptance Prone

In operational networks, requests for channel establishment have diverse demands of bandwidth (number of slots). Each set of contiguously available slots can accommodate a certain number of single demands. For example, two contiguous slots can accommodate demands of 1 and demands of 2 slots. The Acceptance Prone function computes the average fraction of demands each set of contiguous available slots can accommodate.

Let
$f_{u,v,i}$ indicates whether or not a contiguous set of available slots starts at slot i
$F_{u,v,n}$ gives the number of sets of contiguous available slots in the spectrum

$$f_{u,v,i} = \begin{cases} 1 & if\ m_{u,v,i}>0 \\ 0 & otherwise \end{cases} \tag{6}$$

$$F_{u,v,n} = \sum_{i=n}^{n+b-1} f_{u,v,i} \tag{7}$$

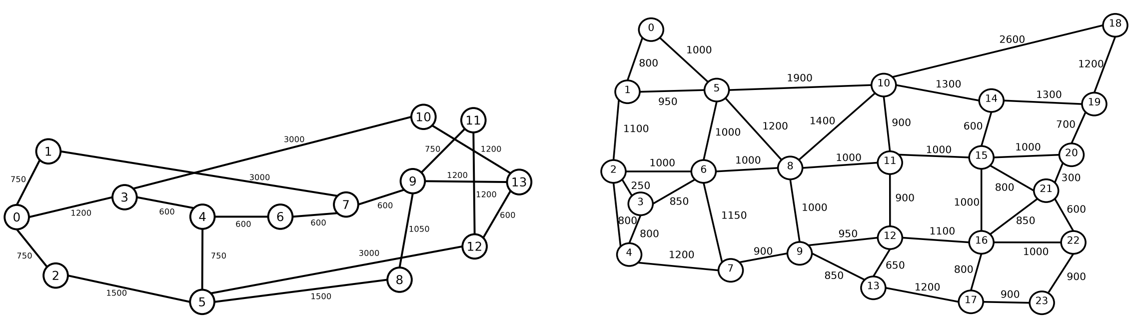
The Acceptance Prone function is given by:

$$\widetilde{c}_n(\widetilde{e}_{\widetilde{u},\widetilde{v}}) = 1 - \frac{1}{F_{u,v,n}} \sum_{i=n}^{n+b-1} \frac{m_{u,v,i}}{N} \tag{8}$$

In this paper, it is assumed that $b = 1 \ldots N$ and that each demand has the same probability to be requested. However, the Acceptance Prone cost function can be easily changed to deal with a different set of demands as well different proportions of these demands.

5 Numerical Evaluation

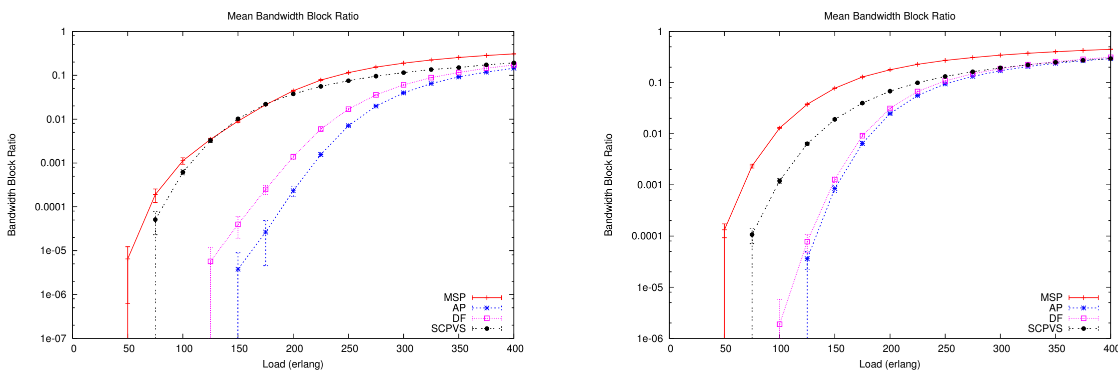
To assess the performance of the multigrapgh shortest path algorithm jointly with the proposed cost functions, simulation experiments were employed and results compared with those given by the MSP and SCPVS algorithms since these algorithms do not consider any metric related to fragmentation. The FlexGridSim [11] simulator was used. In each simulation, 100,000 requests were generated and simulations for each algorithms used the same set of seeds. Confidence intervals with 95% confidence level were generated. The NSF (Figura 2(a)) and the USA (Figura 2(b)) topologies were used. The NSF toplogy has 16 nodes and 25 links whereas the USA topology has 24 nodes and 43 links. In the simulated elastic network, the spectrum was divided in 240 slots of 12,5GHz each.



(a) The NSF topology (b) The USA topology

Figure 2: Used Topologies

Figure 3(a) displays the bandwidth blocking ratio (BBR) as a function of the load for the USA topology. The load was increased in units of 25 erlangs for all the figures in the paper. Requests arrive according to a Poisson process and connection holding time are exponentially distributed. The mean arrival rate and the mean holding time are adjusted to simulated the desired load in erlangs. While MSP and SCPVS start blocking request under loads of 50 and 75 erlangs, respectively, DF and AP start blocking only under loads of 125 and 150 erlangs. MSP and SCPVS produce bandwidth blocking ratio two order of magnitude lower under 200 erlangs. Under loads of 300 and higher the BBR produced by them and by SCPVS is the same but even under loads of 400, the difference is still of 50%. Such lower BBR produced by DF and AP evinces the benefit of considering the spectrum fragmentation state when choosing the route and part of the spectrum to allocate to a new request. Such consideration produces less fragmented spectrum and consequently the probability of blocking future requests decreases. When comparing the two proposed cost functions, AP produces BBR one order of magnitude lower until under loads of 200 erlangs, after that, the difference decreases and they converge to the same value only under very high loads of 400 erlangs.



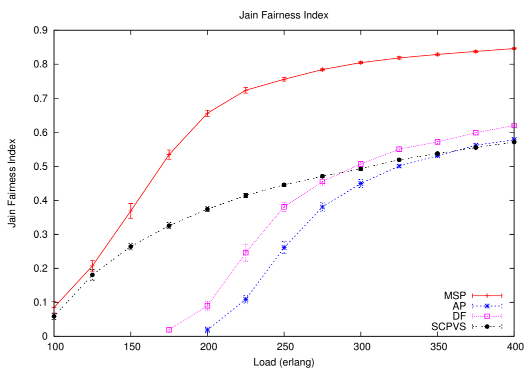
(a) Bandwidth Blocking Ratio as a function of the load for the USA topology

(b) Bandwidth Blocking Ratio as a function of the load for the NSF topology

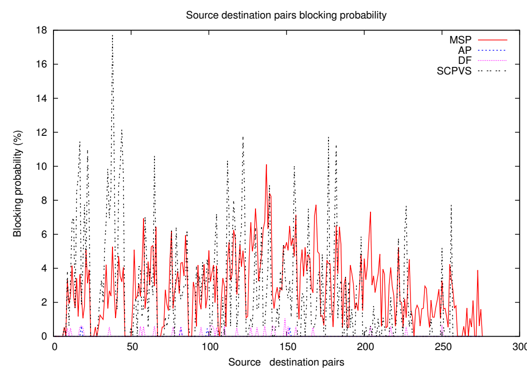
Figure 3: Bandwidth Blocking Ratio

Figure 3(b) shows the bandwidth blocking ratio for the NSF topology. DF and AP start blocking under loads of 25 erlangs lower than they did for the USA topology. This happen due to less alternative paths in the NSF topology to avoid blocking. When DF and AP start blocking request, the BBR produced by them is four order of magnitude lower than that given by the MSP , and three order of magnitude lower than that given by SCPV. The BBR given by DF and AP is one order of magnitude lower than that given by the SCPV until loads of 150 erlangs and until loads of 200 erlangs when compared to that produced by the MSP. Under loads higher than 300 erlangs, a 50% difference in BBR values exists between those given by the proposed algorithms and those given by the MSP. The BBR produced by the proposed functions are roughly the same but the AP start blocking under a load of 25 erlangs higher. Such results reinforce that the consideration of the fragmentation state of the network significantly decrease the bandwidth blocking ratio.

Figure 4(a) displays the Jain Index of Fairness of the BBR experienced by different source destination pairs for the USA topology. The MSP blocking has the high Jain index values, distributing the blocking of requests more uniformly among the source destination pairs. Indeed this happens only because the MSP produces much greater blocking as reported in the previous two figures. MF and AP produce low Jain Index of fairness since several source destination pairs do not face blocking, especially under low loads. This can be observed in Figure 4(b) in which the BBR for each pair was plotted for a single simulation run. As can be seen the large difference in BBR implies that requests for several source destination pairs do not face blocking. The Jain index of fairness for the SCPVS is lower than that of the MSP for a different reason; the SCPVS produces large differences in BBR for those pairs which have their requests blocked. The Jain index value produced by DF is 0.1 higher than that given by AP until loads of 250 erlangs. Such difference can be explained by the difference in blocking produced by the two algorithms.



(a) Jain Fairness Index of Fairness as a function of the load for the NSF topology



(b) Bandwidth Blocking Ratio per S-D pair under 200 erlangs for the NSF topoloy

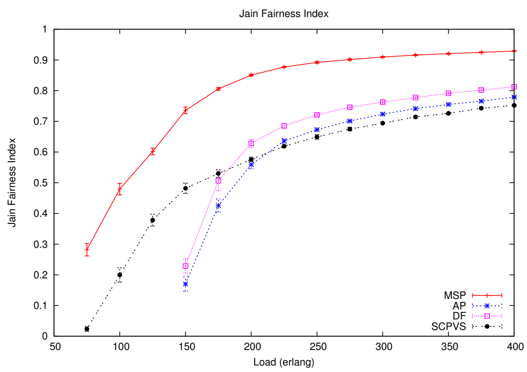
Figure 4: Fairness

Figure 5(a) shows the Jain index of fairness for the NSF toplogy. Since this topology has less alternative paths and leads to higher BBR values, the Jain index of fairness is higher than those produced for the USA topology because more source destination pairs experience blocking. This can be seen when comparing the blocking for each individual pair for the two topologies. In Figure 5(b), the curves for DF and AP are much more visible than in Figure 4(b).

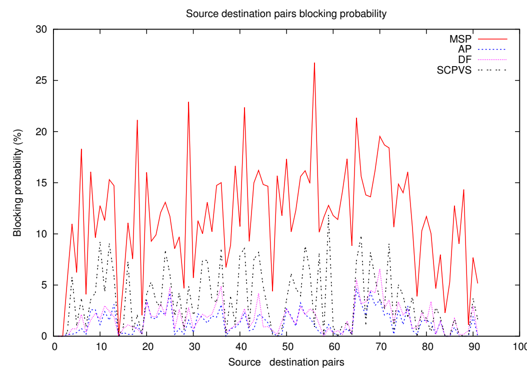
Figures 6(a) and 6(b) plot the average number of hops of the lightpaths established. As can be seen for both topologies, the difference in hops is at most 0.5 which means that the path is one hop longer for every two lightpaths established. Moreover, it shows that DF and AP produces considerably lower blocking using a similar number of hops which evinces that the length of the path is not a major factor contributing to lower BBR values.

6 Conclusion

The great advantage of spectrum allocation at fine granularity in elastic networks can be jeopardized by the fragmentation of the spectrum resulted from the allocation and deallocation of the spectrum. This paper introduced the Multigraph Shortest Path algorithm

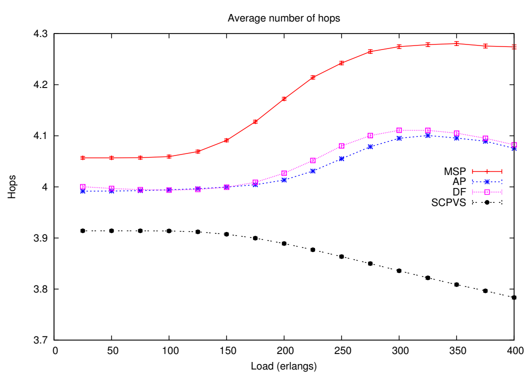


(a) Jain Fairness Index of Fairness as a function of the load for the NSF topology

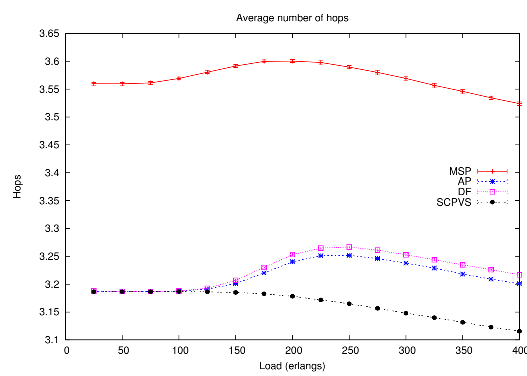


(b) Bandwidth Blocking Ratio per S-D pair under 200 erlangs for the NSF topoloy

Figure 5: Fairness



(a) Average number of hops allocated per lightpath for the USA topology



(b) Average number of hops allocated per lightpath for the USA topology

Figure 6: Number of hops

which represent the spectrum occupancy by a multigraph. Allocation decisions are based on cost functions which try to capture the potentiality of spectrum fragments of allocating incoming requests. The proposed algorithm can produce bandwidth blocking ratio four orders of magnitude lower than those given by existing algorithm. As future work, we plan to include the selection of modulation schemes as well as metrics to make the MSP algorithm energy-aware.

7 Acknowledgments

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References

[1] X. Chen, A. Jukan, A. C. Drummond, and N. L. S. da Fonseca, "A multipath routing mechanism in optical networks with extremely high bandwidth requests," in *Global Telecommunications Conference, 2009. GLOBECOM 2009. IEEE*, pp. 1–6, 2009.

[2] K. Christodoulopoulos, I. Tomkos, and E. Varvarigos, "Elastic bandwidth allocation in flexible ofdm-based optical networks," *Lightwave Technology, Journal of*, vol. 29, pp. 1354 –1366, may1, 2011.

[3] Y. Wang, X. Cao, and Y. Pan, "A study of the routing and spectrum allocation in spectrum-sliced elastic optical path networks," in *INFOCOM, 2011 Proceedings IEEE*, pp. 1503 –1511, april 2011.

[4] L. Velasco, M. Klinkowski, M. Ruiz, and J. Comellas, "Modeling the routing and spectrum allocation problem for flexgrid optical networks," *Photonic Network Communications*, pp. 1–10, 2012. 10.1007/s11107-012-0378-7.

[5] X. Wan, L. Wang, N. Hua, H. Zhang, and X. Zheng, "Dynamic routing and spectrum assignment in flexible optical path networks," in *Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2011 and the National Fiber Optic Engineers Conference*, pp. 1 –3, march 2011.

[6] G. Zhang, M. D. Leenheer, A. Morea, and B. Mukherjee, "A survey on ofdm-based elastic core optical networking," *IEEE COMMUNICATIONS SURVEYS & TUTORIALS*, vol. Volume:PP, Issue: 99, pp. 1–23, 2012.

[7] A. Patel, P. Ji, J. Jue, and T. Wang, "Defragmentation of transparent flexible optical wdm (fwdm) networks," in *Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2011 and the National Fiber Optic Engineers Conference*, pp. 1 –3, march 2011.

[8] R. Wang and B. Mukherjee, "Spectrum management in heterogeneous bandwidth networks," in *Global Communications Conference (GLOBECOM), 2012 IEEE*, pp. 2907–2911, 2012.

[9] R. Wang and B. Mukherjee, "Provisioning in elastic optical networks with non-disruptive defragmentation," in *Optical Network Design and Modeling (ONDM), 2013 17th International Conference on*, pp. 223–228, 2013.

[10] M. Zhang, W. Shi, L. Gong, W. Lu, and Z. Zhu, "Bandwidth defragmentation in dynamic elastic optical networks with minimum traffic disruptions," in *Communications (ICC), 2013 IEEE International Conference on*, 2013.

[11] P. M. Moura and A. C. Drummond, "FlexGridSim: Flexible Grid Optical Network Simulator." http://www.lrc.ic.unicamp.br/FlexGridSim/.