Fragmentation-Aware Routing, Modulation and Spectrum Assignment Algorithms in Elastic Optical Networks

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Abstract: We investigate the principle of how dynamic service provisioning fragments the spectral resources on links along a path, and propose corresponding RMSA algorithms to alleviate spectrum fragmentation in dynamic network environments.
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1. Introduction

Elastic optical networking [1] (EON) is a promising approach to meeting the increasingly diverse traffic demands due to its ability to efficiently utilize spectral resources for optical fiber communication. By replacing the coarse and rigid spectral grid in a typical WDM network (ITU-T G.694.1) with a smaller and more flexible grid, it enables spectrum allocation for each request based on its exact bandwidth demand. However, setting up and tearing down connections with mixed sizes of bandwidths in a dynamic network environment can fragments the spectral resources into non-contiguous small pieces. Spectral resource fragmentation can become a serious problem where large bandwidth requests cannot take advantage of fragmented pieces of spectral resources to set up super-wavelength connections, which inevitably leads to spectrum underutilization and potentially high blocking probability in EON.

Fragmentation in computer memory and storage system is a well-studied problem [2]. However, the unique constraints imposed by EON, such as the joint optimization of routing, modulation format and spectrum assignment (RMSA) in fiber links, distinguish such a problem in EON from that in computer storage systems. Algorithms solving the fragmentation problem in EON can be categorized into reactive defragmentation and active fragmentation aware RMSA. Paper [3-5] addressed different reactive defragmentation schemes in order to improve the spectral resource usability when fragmentation already happened in the EONs. Previous works on dynamic or static RMSA [6-8] barely considered fragmentation as one of the optimization goals, except for paper [9], which tried to minimize fragmentation by maximizing the sizes of common segments in spectrum domain between candidate links and their neighbor links.

In this paper, we investigate the fundamental of how service provisioning fragments the spectral resources on links along a path, and propose corresponding fragmentation-aware RMSA algorithms to alleviate the fragmentation due to service provisioning. As dynamic provisioning can create not only spectrum fragments on the links, but also spectrum misalignments along routing paths, we quantify both fragmentation and alignment with two factors. The proposed algorithms consider these factors to alleviate the negative impact of dynamic service provisioning.

2. Spectrum Fragmentation and Misalignment due to Service Provisioning

Figure 1 shows an example of how the service provisioning process fragments the spectrum resources on fiber links. Suppose we have a 6-node, 8-link mesh network and the spectral resources are distributed as shown in Figure 1(a). For simplicity, we assume there are only 12 spectrum slots on a fiber link in this example. Note that 400 12.5 GHz slots can be accommodated on a 5 THz fiber link. The gray blocks on a link means the corresponding spectral slots that are already occupied by existing connections, while the white blocks means that they are available. When a new request arrives with source address *A* and destination address *E*, the routing algorithm first calculates all possible routes for this connection, resulting in the 4 paths as shown in Figure 1(b). The arrow-headed lines indicate all possible solutions to provision this *A-E* request with one slot bandwidth. Note that different solutions have different costs of "Cut" value, which accounts for the number of spectrum blocks the provisioning scheme will break. For example, the provisioning of the request on path *ABCE* with slot 11 will "Cut" two spectrum blocks on link *BC* and *CE*, namely the empty contiguous block 7-12. Likewise, the other provisioning choices "Cut" different numbers of spectrum blocks. The "broken" spectrum blocks become more fragmented as they lose their continuity in the spectral domain. Therefore, we can consider the number of "Cuts" as the cost of a provisioning. In the example in Figure 1(b), the provisioning choice with solid arrow-headed line give zero "Cut" and therefore it is mostly preferred from fragmentation perspective.

On the other hand, the provisioning of a request can also break the alignment of available spectrum blocks between the candidate links and their neighbor links. The alignment of the available spectrum blocks on two neighbor links creates commonly available spectra and is valuable for future connection requests. For example, the candidate provisioning on path *ADE* on slot 8 will influence the alignment between the neighboring links as shown in Figure 1(c). The misalignment of link pair *BA* and *AD* will increase by 1 since the provisioning on link *AD* on slot 8 (slash block) reduces the commonly available spectra by one slot. Likewise, all the alignment changes of adjacent link pairs along the candidate path *ADE* can be calculated. The misalignment increase is considered as an additional cost related to fragmentation. Therefore, among all candidate solutions, the alignment-aware algorithm should minimize this cost when doing the RMSA provisioning.

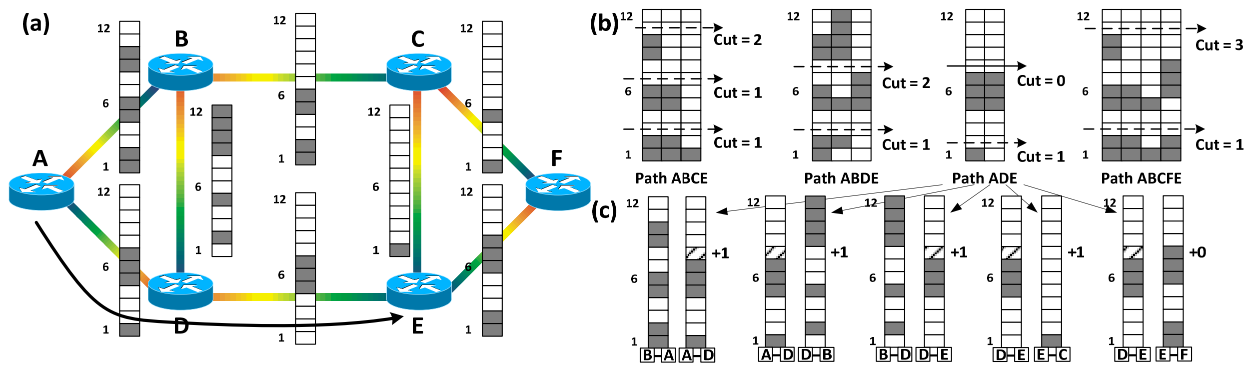

Figure 1. (a) example FISH network and the spectral assignment status on the links, (b) number of "Cuts" to all the candidate solution to connection request *A-E*, and (c) alignment factor increase if choosing path *ADE* with slot 8.

3. Fragmentation- and Alignment-Aware RMSA Algorithms

Taking the advantage of the observations above, we propose fragmentation- and alignment-aware RMSA algorithms respectively. The fragmentation-aware RMSA calculates the number of "Cuts" caused by all RMSA candidates and chooses the one with the minimum number of "Cuts". If there exist more than one RMSA candidates that achieve the identical minimum number of "Cuts", the algorithm use the shortest path and first-fit rule to choose the solution. On the other hand, the alignment-aware RMSA considers minimizing the increase in the misaligned available spectral slots when provisioning the connection requests. If more than one RMSA candidate satisfies the minimum misalignment increase constraint, the algorithm uses the shortest path and first-fit rule to choose the solution. In addition, we also propose a provisioning algorithm that considers both the fragmentation cost and alignment cost jointly. The algorithm, named as P-CF, preselects the all the candidate routes that have at least one spectral block to accommodate the incoming request. Within the preselected set, the algorithm calculates the cost of each RMSA candidates using the formula below:

$$A = (H * S + F_{cut} + M_{align})/C \tag{1}$$

where H means the number of hops for the candidate path, S means number of spectral slots assigned to the candidate route considering the distance adaptive modulation format assignment [10]. F_{cut} and M_{align} respectively represent the number of "Cut" and alignment increase mentioned in Section 2, and C means the number of available spectral slots on current path. The cost of choosing a route becomes higher when there's less spectral resources available on the route. This algorithm combines shortest path routing, fragmentation- and alignment-aware routing and balanced-load spectrum assignment in one step. The algorithm uses first fit rule to assign spectrum when there are more than one RMSA candidates that have the same minimum A. We use simulation tools to evaluate the proposed algorithms and compare them with three existing RMSA algorithms, namely the shortest path routing (SP), the balanced load routing (BLSA) and the preselected k-shortest path routing (P-SP) algorithms [11]. Here "preselected" means the algorithm calculates all the candidate paths first, and then preselects the *k*-shortest routes which have at least one spectral block available for the incoming request

4. Numerical Evaluation

Network simulations have been carried out to compare the performance of the proposed algorithm versus the existing RMSA algorithms. Dynamic connection arrival and departure events are simulated on a 14-node NSFNET network and a 24-node USBN network respectively. Each spectral slot is assumed to be 12.5 GHz and each fiber link has 400 slots. In the simulation, 6,000~10,000 connection requests with randomly chosen source and destinations arrive according to a Poisson process. The holding time of each connection follows an exponential distribution averages at 5 time units. The connection bandwidth requirements randomly distributed in the set of line rates *L*={10 Gb/s, 20 Gb/s, 40 Gb/s, 80 Gb/s, 100 Gb/s, 160 Gb/s, 200 Gb/s, 400 Gb/s, 800 Gb/s, 1 Tb/s}, and the actual spectrum slot number requirement is calculated after the modulation format is assigned according to the distance of the connection [10].

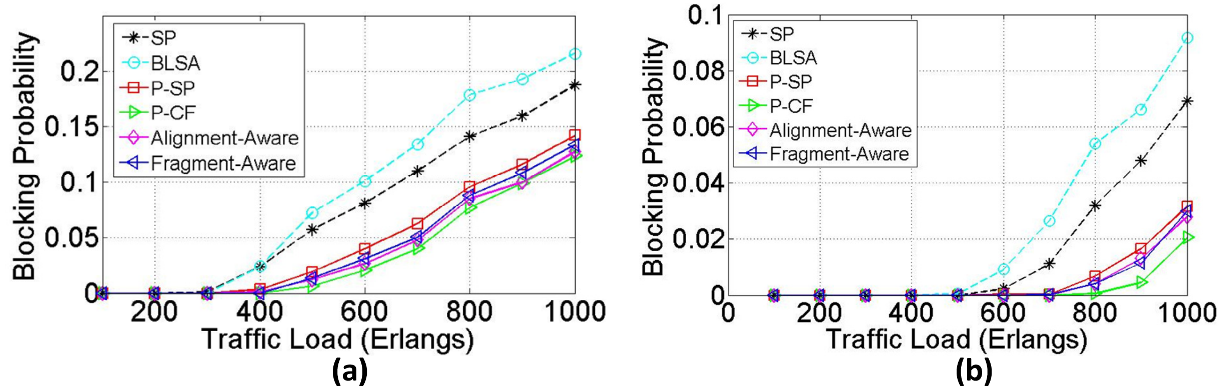

Figure 2. Blocking probability comparison of different algorithms in the (a) 14-node NSFNET network (b) 24-node USBN network.

Figure 2 (a) shows the blocking probability comparison using different RMSA provision algorithms in the dynamic traffic scenario. The proposed fragmentation-aware and alignment-aware algorithms significantly outperform the existing SP and BLSA algorithms in terms of blocking probability. In particular, the P-CF algorithm can reduce the blocking probability by a factor of 2 on the average compared to the shortest-path routing and first fit spectrum assignment algorithm. Moreover, the alignment-aware algorithm performs slightly better than the fragmentation-aware algorithm, which reveals the fact that the misalignment of empty spectral slots in link dimension creates more stranded bandwidth than discrete spectral slots in wavelength dimension in a network without spectrum conversion capabilities. The P-CF algorithm performs the best in reducing blocking probabilities since it considers not only the fragmentation and misalignment factor, but also the shortest path and load balanced routing, which compromises the trade-off between minimizing fragmentation and minimizing the overall resource consumption. Simulations on USBN network in Figure 2 (b) shows similar results.

4. Conclusion

In this paper, we analyzed the fragmentation problem in detail for service provisioning in dynamic elastic optical networks, and proposed three fragmentation-aware algorithms for routing, modulation and spectrum assignment (RMSA) in elastic optical networks. The proposed RMSA algorithms outperformed the existing ones in terms of blocking probability as they could proactively reduce spectral fragments in the network. Therefore, they released the potential capacity in the network, which would otherwise become stranded. The proposed schemes complemented the reactive defragmentation methods studied in [3-5].

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References

[1] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, and S. Matsuoka, "Spectrum-Efficient and Scalable Elastic Optical Path Network: Architecture, Benefits, and Enabling Technologies," *IEEE Commun. Mag.,* vol. 47, pp. 66-73, 2009.

[2] D. E. Knuth, *The Art of Computer Programming, Fundamental Algorithms*, 3 ed. vol. 1: Addison-Wesley, 1973.

[3] A. N. Patel, Philip N. Ji, Jason P. Jue, and T. Wang, "Defragmentation of Transparent Flexible Optical WDM (FWDM) Networks," in *OFC/NFOEC*, Los Angeles, 2011.

[4] H. H. T. Takagi, Ken-ichi Sato, Y. Sone, A. Hirano, and M. Jinno, "Disruption Minimized Spectrum Defragmentation in Elastic Optical Path Networks that Adopt Distance Adaptive Modulation," in *ECOC 2011*, Geneva, 2011.

[5] Yawei Yin, Ke Wen, David J. Geisler, Ruiting Liu, and S. J. B. Yoo, "Dynamic On-demand Defragmentation in Flexible Bandwidth Elastic Optical Networks," *Optics Express,* vol. 20, pp. 1798-1804, January, 2012 2012.

[6] M. Jinno, B. Kozicki, H. Takara, A. Watanabe, Y. Sone, T. Tanaka*, et al.*, "Distance-adaptive Spectrum Resource Allocation In Spectrum-sliced Elastic Optical Path Network," *IEEE Commun. Mag.,* pp. 138-45, 2010.

[7] I. T. K. Christodoulopoulos, and E. A. Varvarigos., "Elastic Bandwidth Allocation in Flexible OFDM-based Optical Networks," *J. Lightwave Technol.,* vol. 29, pp. 1354-1366, 2011.

[8] T. Takagi, H. Hasegawa, K.-i. Sato, Y. Sone, B. Kozicki, A. Hirano*, et al.*, "Dynamic Routing and Frequency Slot Assignment for Elastic Optical Path Networks that Adopt Distance Adaptive Modulation," in *Optical Fiber Communication Conference*, 2011, p. OTuI7.

[9] Y. Sone, A. Hirano, A. Kadohata, M. Jinno, and O. Ishida, "Routing and spectrum assignment algorithm maximizes spectrum utilization in optical networks," in *Optical Communication (ECOC), 2011 37th European Conference and Exhibition on*, 2011, pp. 1-3.

[10] S. Dahlfort, M. Xia, R. Proietti, and S. J. B. Yoo, "Split Spectrum Approach to Elastic Optical Networking," in *38th European Conference and Exposition on Optical Communications*, 2012, p. Tu.3.D.4.

[11] X. C. Yang Wang, and Yi Pan, "A study of the routing and spectrum allocation in spectrum-sliced Elastic Optical Path networks," in *INFOCOM 2011*, 2011, pp. 1503-1511.