Spectrum Defragmentation in Elastic Optical Networks

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***Abstract*—Elastic optical networks (EONs) provide fine bandwidth allocation granularity and enable scalable network management. In this paper, we review the strategies to alleviate spectrum fragmentation from both the preemptive and proactive perspectives. As for preemptive defragmentation, we investigate the characteristics of bandwidth fragmentation in EONs, and then discuss a fragmentation-aware routing and spectrum assignment (RSA) algorithm to relieve spectrum fragmentation when setting up connections. As for proactive defragmentation, we decompose the problem into three subproblem: 1) *Connection Selection*; 2) *RSA Re-optimization*; and 3) *Traffic Migration*. We also discuss the problem of timing selection for defragmentation in dynamic network environments, and investigate how to improve network performance with the minimum operation cost by using intelligent and adaptive timing selection.**

***Index Terms*—EONs, bandwidth fragmentation, defragmentation, network reconfiguration**

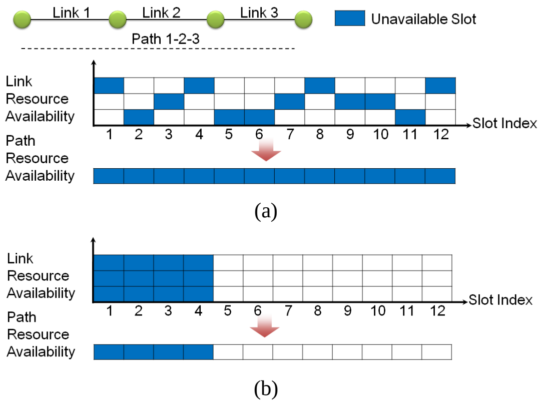

Fig. 1. An example of bandwidth defragmentation in EONs.

I. Introduction

A new era of optical network can be foreseen with the advances of elastic optical networking that adopts the optical orthogonal frequency-division multiplexing multiplexing (O-OFDM) technology [1–41]. It is known that with O-OFDM, the bandwidth allocation granularity can be reduced down to 12.5GHz or less. Therefore, elastic optical networks (EONs) built with O-OFDM can realize more agile bandwidth management than the wavelength-division multiplexing (WDM) networks. However, the flexible nature of EONs also brings new challenges for network operators. One important example is the spectrum fragmentation, which refers to the existing of non-aligned, isolated and small-sized blocks of spectral segments in EONs due to setting up and tearing down connections frequently [3, 11]. Spectrum fragmentation has serious consequences, as it can lead to low bandwidth utilization and high blocking probability.

To alleviate spectrum fragmentation, one can seek the solutions with either preemptive or proactive strategies. Preemptive strategies refer to designing routing and spectrum assignment (RSA) algorithms with the objective to minimizing spectrum fragmentation during setting up requests [42–63]. These type of RSA algorithms can be called as fragmentation-aware RSA [4, 6]. However, there is no guarantee that the fragmentation-aware RSA can eliminate spectrum fragmentation. Therefore, proactive strategies with spectrum defragmentation have also been proposed [3, 4, 6, 13]. Typically, spectrum defragmentation involves the rerouting and retuning of some existing connections to consolidate the spectrum utilization. Fig. 1 shows an intuitive example of spectrum defragmentation. Consider that we have a routing path that consists of three fiber links, *i.e.*, L_1, L_2, and L_3, Fig. 1(a) and 1(b) show the spectrum utilization before and after defragmentation. The spectrum defragmentation consolidates the available spectrum fragments and vacates spectrum resources over the path for future requests.

In this paper, we review both the preemptive and proactive strategies for alleviating spectrum fragmentation in EONs. The rest of the paper is organized as follows. The preemptive strategies, *i.e.*, the fragmentation-aware RSA algorithms, are discussed in Section II, while the proactive ones, *i.e.*, the spectrum defragmentation algorithms, are reviewed in Section III. Finally, Section IV summarizes the paper.

II. Fragmentation-Aware RSA Algorithms

Spectrum fragmentation can be caused by two factors during RSA: 1) when allocating a block of contiguous spectrum to a request, we may cut the available spectrum on fiber links into small segments. 2) RSA leads to the situation that the available spectrum on a certain link is misaligned in the spectrum domain with those on the neighbor links. The objective of fragmentation-aware RSA is to minimize these two factors during RSA. In [3], we proposed a fragmentation-aware RSA algorithm, and the simulation results showed that the fragmentation-aware RSA algorithm can reduce request blocking probability significantly, compared with other RSA

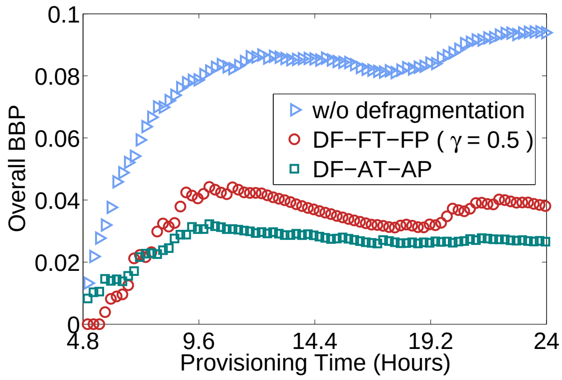

Fig. 2. Overall bandwidth blocking probability (BBP) versus provision time [35].

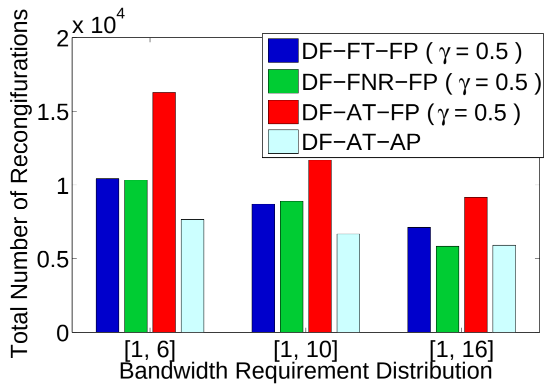

Fig. 3. Total number of connection reconfigurations within a 24-hour period [35].

algorithms that did not consider spectrum fragmentation.

III. Spectrum Defragmentation Algorithms

Spectrum defragmentation involves the reconfiguration of existing connections to consolidate the spectrum utilization. More specifically, each defragmentation operation consists of three steps.

- *Step 1*: Select existing connections for reconfiguration.
- *Step 2*: Redo RSA the selected connections to consolidate spectrum utilization.
- *Step 3*: Migrate the connections to new RSA locations.

With these steps, the simulation results in [6] showed that bandwidth defragmentation can reduce blocking probability effectively. Besides the benefits brought by defragmentation on network performance, it is also necessary to consider the operation cost of defragmentation. Untimely defragmentation cannot reduce the blocking probability to an acceptable level, while too frequent defragmentation can lead to unnecessary operation cost. We need to leverage the network status information, and make the defragmentation timing selection intelligently and adaptively.

We assume that the EON's traffic load varies in an unpredictable but gradual manner, and monitor the network status to achieve intelligent defragmentation timing selection. When we observe the upward trend of request blocking probability, we will shorten the time interval for next defragmentation, otherwise, we take the opposite action. However, in the situation where the blocking is in a relative low level or even no blocking, although the trend of blocking can be upward, it is not necessary to trigger defragmentation. We realize this by setting a blocking time window that can be changed dynamically [35]. The simulation results in Fig. 2 and Fig. 3 showed that the defragmentation strategy that adopts both adaptive time and object selection strategies (DF-AT-AP) not only achieved maximum bandwidth blocking probability (BBP) reduction but also invoked the minimum times of reconfigurations for defragmentation.

IV. Conclusion

In this paper, we reviewed both the preemptive and proactive strategies for alleviating spectrum fragmentation in EONs. For preemptive defragmentation, we discussed a fragmentation-aware RSA algorithm to relieve spectrum fragmentation when setting up new connections. For proactive defragmentation, we considered to involve reconfiguration of existing connections to consolidate the spectrum utilization. Defragmentation in dynamic network environment with intelligent timing selection was also discussed.

References

[1] Z. Zhu, W. Lu, L. Zhang, and N. Ansari, "Dynamic service provisioning in elastic optical networks with hybrid single-/multi-path routing," *J. Lightw. Technol.*, vol. 31, pp. 15–22, Jan. 2013.

[2] L. Gong, X. Zhou, W. Lu, and Z. Zhu, "A two-population based evolutionary approach for optimizing routing, modulation and spectrum assignments (RMSA) in O-OFDM networks," *IEEE Commun. Lett.*, vol. 16, pp. 1520–1523, Sept. 2012.

[3] Y. Yin, M. Zhang, Z. Zhu, and S. Yoo, "Fragmentation-aware routing, modulation and spectrum assignment algorithms in elastic optical networks," in *Proc. of OFC 2013*, pp. 1–3, Mar. 2013.

[4] Y. Yin *et al.*, "Spectral and spatial 2D fragmentation-aware routing and spectrum assignment algorithms in elastic optical networks," *J. Opt. Commun. Netw.*, vol. 5, pp. A100–A106, Oct. 2013.

[5] L. Gong *et al.*, "Efficient resource allocation for all-optical multicasting over spectrum-sliced elastic optical networks," *J. Opt. Commun. Netw.*, vol. 5, pp. 836–847, Aug. 2013.

[6] M. Zhang *et al.*, "Bandwidth defragmentation in dynamic elastic optical networks with minimum traffic disruptions," in *Proc. of ICC 2013*, pp. 3894–3898, Jun. 2013.

[7] W. Lu and Z. Zhu, "Dynamic service provisioning of advance reservation requests in elastic optical networks," *J. Lightw. Technol.*, vol. 31, pp. 1621–1627, May 2013.

[8] L. Gong, W. Zhao, Y. Wen, and Z. Zhu, "Dynamic transparent virtual network embedding over elastic optical infrastructures," in *Proc. of ICC 2013*, pp. 3466–3470, Jun. 2013.

[9] W. Lu *et al.*, "Dynamic multi-path service provisioning under differential delay constraint in elastic optical networks," *IEEE Commun. Lett.*, vol. 17, pp. 158–161, Jan. 2013.

[10] L. Liu *et al.*, "Software-defined fragmentation-aware elastic optical networks enabled by OpenFlow," in *Proc. of ECOC 2013*, pp. 1–3, Sept. 2013.

[11] W. Shi, Z. Zhu, M. Zhang, and N. Ansari, "On the effect of bandwidth fragmentation on blocking probability in elastic optical networks," *IEEE Trans. Commun.*, vol. 61, pp. 2970–2978, Jul. 2013.

[12] L. Gong and Z. Zhu, "Virtual optical network embedding (VONE) over elastic optical networks," *J. Lightw. Technol.*, vol. 32, pp. 450–460, Feb. 2014.

[13] M. Zhang, C. You, H. Jiang, and Z. Zhu, "Dynamic and adaptive bandwidth defragmentation in spectrum-sliced elastic optical networks with time-varying traffic," *J. Lightw. Technol.*, vol. 32, pp. 1014–1023, Mar. 2014.

[14] X. Zhou, W. Lu, L. Gong, and Z. Zhu, "Dynamic RMSA in elastic optical networks with an adaptive genetic algorithm," in *Proc. of GLOBECOM 2012*, pp. 2912–2917, Dec. 2012.

[15] F. Ji *et al.*, "Dynamic p-cycle protection in spectrum-sliced elastic optical networks," *J. Lightw. Technol.*, vol. 32, pp. 1190–1199, Mar. 2014.

[16] X. Liu, L. Gong, and Z. Zhu, "On the spectrum-efficient overlay multicast in elastic optical networks built with multicast-incapable switches," *IEEE Commun. Lett.*, vol. 17, pp. 1860–1863, Sept. 2013.

[17] L. Yang *et al.*, "Leveraging light-forest with rateless network coding to design efficient all-optical multicast schemes for elastic optical networks," *J. Lightw. Technol.*, vol. 33, pp. 3945–3955, Sept. 2015.

[18] S. Shen *et al.*, "Dynamic advance reservation multicast in data center networks over elastic optical infrastructure," in *Proc. of ECOC 2013*, pp. 1–3, Sept. 2013.

[19] W. Lu *et al.*, "Implementation and demonstration of revenue-driven provisioning for advance reservation requests in OpenFlow-controlled SD-EONs," *IEEE Commun. Lett.*, vol. 18, pp. 1727–1730, Oct. 2014.

[20] W. Lu and Z. Zhu, "Malleable reservation based bulk-data transfer to recycle spectrum fragments in elastic optical networks," *J. Lightw. Technol.*, vol. 33, pp. 2078–2086, May 2015.

[21] M. Zhang *et al.*, "Spectrum defragmentation algorithms for elastic optical networks using hitless spectrum retuning techniques," in *Proc. of OFC 2013*, pp. 1–3, Mar. 2013.

[22] Z. Zhu *et al.*, "OpenFlow-assisted online defragmentation in single-/multi-domain software-defined elastic optical networks," *J. Opt. Commun. Netw.*, vol. 7, pp. A7–A15, Jan. 2015.

[23] L. Zhang and Z. Zhu, "Dynamic anycast in inter-datacenter networks over elastic optical infrastructure," in *Proc. of ICNC 2014*, pp. 491–495, Feb. 2014.

[24] X. Liu, L. Gong, and Z. Zhu, "Design integrated RSA for multicast in elastic optical networks with a layered approache," in *Proc. of GLOBECOM 2013*, pp. 2346–2351, Dec. 2013.

[25] X. Chen, F. Ji, and Z. Zhu, "Service availability oriented p-cycle protection design in elastic optical networks," *J. Opt. Commun. Netw.*, vol. 6, pp. 901–910, Oct. 2014.

[26] L. Zhang, W. Lu, X. Zhou, and Z. Zhu, "Dynamic RMSA in spectrum-sliced elastic optical networks for high-throughput service provisioning," in *Proc. of ICNC 2013*, pp. 380–384, Jan. 2014.

[27] C. Chen *et al.*, "Demonstration of OpenFlow-controlled cooperative resource allocation in a multi-domain SD-EON testbed across multiple nations," in *Proc. of ECOC 2014*, pp. 1–3, Sept. 2014.

[28] W. Lu, X. Zhou, L. Gong, and Z. Zhu, "Scalable network planning for elastic optical orthogonal frequency division multiplexing (OFDM) networks," in *Proc. of CSNDSP 2012*, pp. 1–4, Jul. 2012.

[29] L. Liu, Z. Zhu, and S. Yoo, "3D elastic optical networks in temporal, spectral and spatial domains with fragmentation-aware RSSMA algorithms," in *Proc. of ECOC 2014*, pp. 1–3, Sept. 2014.

[30] L. Zhang and Z. Zhu, "Spectrum-efficient anycast in elastic optical inter-datacenter networks," *Opt. Switch. Netw.*, vol. 14, pp. 250–259, Aug. 2014.

[31] X. Liu, L. Zhang, M. Zhang, and Z. Zhu, "Joint defragmentation of spectrum and computing resources in inter-datacenter networks over elastic optical infrastructure," in *Proc. of ICC 2014*, pp. 3289–3294, Jun. 2014.

[32] Z. Zhu *et al.*, "Demonstration of cooperative resource allocation in an OpenFlow-controlled multidomain and multinational SD-EON testbed," *J. Lightw. Technol.*, vol. 33, pp. 1508–1514, Apr. 2015.

[33] C. You, M. Zhang, and Z. Zhu, "Reduce spectrum defragmentation latency in EONs with effective parallelization of connection reconfigurations," in *Proc. of OFC 2014*, pp. 1–3, Mar. 2014.

[34] F. Ji *et al.*, "Dynamic p-cycle configuration in spectrum-sliced elastic optical networks," in *Proc. of GLOBECOM 2013*, pp. 2170–2175, Dec. 2013.

[35] M. Zhang *et al.*, "Adaptive spectrum defragmentation with intelligent timing and object selection for elastic optical networks with time-varying traffic," in *Proc. of ECOC 2013*, pp. 1–3, Sept. 2013.

[36] X. Chen *et al.*, "Flexible availability-aware differentiated protection in software-defined elastic optical networks," *J. Lightw. Technol.*, vol. 33, pp. 3872–3882, Sept. 2015.

[37] X. Chen, S. Zhu, L. Jiang, and Z. Zhu, "On spectrum efficient failure-independent path protection p-cycle design in elastic optical networks," *J. Lightw. Technol.*, vol. 33, pp. 3719–3729, Sept. 2015.

[38] X. Chen *et al.*, "On efficient protection design for dynamic multipath provisioning in elastic optical networks," in *Proc. of ONDM 2015*, pp. 251–256, May 2015.

[39] W. Fang *et al.*, "Joint defragmentation of optical spectrum and IT resources in elastic optical datacenter interconnections," *J. Opt. Commun. Netw.*, vol. 7, pp. 314–324, Mar. 2015.

[40] X. Chen *et al.*, "Leveraging master-slave openflow controller arrangement to improve control plane resiliency in SD-EONs," *Opt. Express*, vol. 23, pp. 7550–7558, Mar. 2015.

[41] W. Lu, Z. Zhu, and B. Mukherjee, "Data-oriented malleable reservation to revitalize spectrum fragments in elastic optical networks," in *Proc. of OFC 2015*, pp. 1–3, Mar. 2015.

[42] Z. Zhu *et al.*, "RF photonics signal processing in subcarrier multiplexed optical-label switching communication systems," *J. Lightw. Technol.*, vol. 21, pp. 3155–3166, Dec. 2003.

[43] ——, "10,000-hop cascaded in-line all-optical 3R regeneration to achieve 1,250,000-km 10-Gb/s transmission," *IEEE Photon. Technol. Lett.*, vol. 18, pp. 718–720, Mar. 2006.

[44] Z. Pan *et al.*, "Demonstration of variable-length packet contention resolution and packet forwarding in an optical-label switching router," *IEEE Photon. Technol. Lett.*, vol. 16, pp. 1772–1774, Jul. 2004.

[45] ——, "Advanced optical-label routing system supporting multicast, optical TTL, and multimedia applications," *J. Lightw. Technol.*, vol. 23, pp. 3270–3281, Oct. 2005.

[46] Z. Zhu *et al.*, "High-performance optical 3R regeneration for scalable fiber transmission system applications," *J. Lightw. Technol.*, vol. 25, pp. 504–511, Feb. 2007.

[47] Z. Zhu, Z. Pan, and S. Yoo, "A compact all-optical subcarrier label-swapping system using an integrated EML for 10-Gb/s optical label-switching networks," *IEEE Photon. Technol. Lett.*, vol. 17, pp. 426–428, Feb. 2005.

[48] Z. Zhu *et al.*, "Jitter and amplitude noise accumulations in cascaded all-optical regenerators," *J. Lightw. Technol.*, vol. 26, pp. 1640–1652, Jun. 2008.

[49] ——, "Energy-efficient translucent optical transport networks with mixed regenerator placement," *J. Lightw. Technol.*, vol. 30, pp. 3147–3156, Oct. 2012.

[50] M. Funabashi *et al.*, "Cascadability of optical 3R regeneration for NRZ format investigated in recirculating loop transmission over field fibers," *IEEE Photon. Technol. Lett.*, vol. 18, pp. 2081–2083, Oct. 2006.

[51] Z. Pan, H. Yang, Z. Zhu, and S. Yoo, "Demonstration of an optical-label switching router with multicast and contention resolution at mixed data rates," *IEEE Photon. Technol. Lett.*, vol. 18, pp. 307–309, Jan. 2006.

[52] Z. Zhu, "Mixed placement of 1R/2R/3R regenerators in translucent optical networks to achieve green and cost-effective design," *IEEE Commun. Lett.*, vol. 15, pp. 752–754, Jul. 2011.

[53] M. Funabashi *et al.*, "Optical clock recovery and 3R regeneration for 10-Gb/s NRZ signal to achieve 10,000-hop cascadability and 1,000,000-km transmission," *IEEE Photon. Technol. Lett.*, vol. 18, pp. 2078–2080, Oct. 2006.

[54] J. Cao *et al.*, "Error-free multi-hop cascaded operation of optical label switching routers with all-optical label swapping," in *Proc. of OFC 2003*, pp. 1–3, Mar. 2003.

[55] ——, "11-hop operation of optical-label switching system with all-optical label swapping," in *Proc. of ECOC 2003*, pp. 1–3, Sept. 2003.

[56] Z. Zhu *et al.*, "1000 cascaded stages of optical 3R regeneration with SOA-MZI-based clock enhancement to achieve 10-Gb/s 125,000-mm dispersion uncompensated transmission," *IEEE Photon. Technol. Lett.*, vol. 18, pp. 2159–2161, Oct. 2006.

[57] Z. Pan *et al.*, "Experimental demonstration of variable-size packet contention resolution and switching in an optical-label switching router," in *Proc. of OFC 2004*, pp. 1–3, Mar. 2004.

[58] ——, "All-optical label swapping, clock recovery, and 3R regeneration in 101-hop cascaded optical-label switching router networks," *IEEE Photon. Technol. Lett.*, vol. 18, pp. 2629–2631, Dec. 2006.

[59] ——, "101-hop cascaded operation of an optical-label switching router with all-optical clock recovery and 3R regeneration," *IEEE Photon. Technol. Lett.*, vol. 18, pp. 1654–1656, Aug. 2006.

[60] Z. Pan, H. Yang, Z. Zhu, and S. Yoo, "Experimental demonstration of a multicast-capable optical-label switching router," in *Proc. of OFC 2005*, pp. 1–3, Mar. 2005.

[61] Y. Jin, Y. Wen, Q. Chen, and Z. Zhu, “An empirical investigation of the impact of server virtualization on energy efficiency for green data center,” *Comput. J.*, vol. 56, pp. 977–990, Aug. 2013.
[62] Z. Zhu, W. Zhong, and C. Wan, “Joint optimization of mixed regenerator placement and wavelength assignment for green translucent optical networks,” in *Proc. of ACP 2011*, pp. 1–3, Nov. 2011.
[63] J. Yao, P. Lu, and Z. Zhu, “Minimizing disaster backup window for geo-distributed multi-datacenter cloud systems,” in *Proc. of ICC 2014*, pp. 3631–3635, Jun. 2014.