Dynamic Multipath Routing With Traffic Grooming in OFDM-Based Elastic Optical Path Networks

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***Abstract*—Elastic optical networks employ flexible routing and spectrum allocation algorithms to support diverse services and heterogeneous traffic. By splitting a traffic request into multiple small-size subconnections and individually transmitting them through several optical paths, multipath routing algorithms can more flexibly utilize spectrum resources than single-path routing algorithms in dynamic scenario. However, due to the imperfect shape of optical filters deployed in the network, guard bands are typically inserted between two adjacent connections in spectrum domain and, thus, cannot be used to transmit data. When the traffic load is heavy, multipath algorithms severely suffer this spectrum waste from deploying many subconnections and result in lower spectrum efficiency than single-path routing. Moreover, multipath routing algorithms require more bandwidth-variable transponders (BVT), which may lead to a higher cost. In this paper, we propose a dynamic multipath routing algorithm with traffic grooming (MPTG) to tackle this problem of multipath routing under heavy traffic load. By aggregating small-size connections originated from the same source node and sharing common fiber links, traffic grooming enhances the network throughput, and also effectively reduce the BVT consumption. The simulation results show that our proposed MPTG algorithm dramatically reduced bandwidth blocking ratio and BVT usage compared with previous multipath routing algorithm.**

***Index Terms*—Dynamic routing and spectrum allocation, elastic optical networks, multipath routing, traffic grooming.**

I. Introduction

RECENT advances in optical transmission technologies have greatly improved the transmission rate in optical networks. Along with the increasing optical transmission rate, low speed applications (e.g., 10 Gb/s) could co-exist with ultra-high speed ones (e.g., 400 Gb/s), which require quite different ranges of bandwidth. However, traditional wavelength division multiplexing (WDM) networks assign fixed bandwidth (e.g., 50 GHz) to each traffic connection. In this way, low speed applications may utilize only part of assigned bandwidth, while ultra-high speed applications may be split into multiple connections and may still suffer spectrum waste as low speed ones do [1]. Due to this rigid coarse granularity, traditional WDM networks are not able to efficiently accommodate heterogeneous traffic. Therefore, more flexible network infrastructures are highly desirable. Elastic optical networks (EONs) have been evolved as the next-generation optical networks with finer granularity (e.g., 12.5 GHz) and truncate the original WDM wavelength channels into spectrum slots. In EON, appropriate number of consecutive spectrum slots is allocated to each traffic connection. Thus, EON can serve heterogeneous traffic in a spectrum-efficient manner [2].

To realize the flexibility introduced by EON, optical orthogonal frequency division multiplexing (O-OFDM) is a promising technology, which loads traffic data onto multiple orthogonal and spectrum-overlapped sub-carriers in order to achieve high spectrum efficiency [3]. Then bandwidth-variable transponders (BVT) with tunable central frequency can elastically accommodate diverse traffic connections by generating appropriate number of O-OFDM sub-carriers [4]. In EON, several consecutive spectrum slots rather than single wavelength channel could be allocated to one connection. Thus, EON requires more sophisticated spectrum resource allocation algorithms than those designed for traditional WDM networks, which are referred as routing and spectrum allocation (RSA) algorithms [5].

In the design of RSA algorithms, spectrum continuity and spectrum contiguity are two key constraints which guarantee that spectrum slots allocated to the same traffic request should be contiguous and kept unchanged along the entire optical path. In static networks, spectrum slots are allocated once and kept unchanged [6]. While in dynamic scenario, spectrum slots are allocated and released according to random arrival and departure with various durations of traffic requests. However, after a large-bandwidth connection terminated, a smaller connection may arrive and occupy only part of the released spectrum slots. Due to the above constraints, the remaining spectrum slots may lower the probability of the successful accommodation for future connections, which is known as spectrum fragmentation. In this case, connections may be blocked though the links have enough available bandwidth resources in total, which are separately located at different ranges of entire spectrum. Therefore, spectrum fragmentation is a critical issue in EON, which degrades the spectrum utilization and network performance. Several studies have concerned about spectrum fragmentation issue [7]–[9]. In [7], authors proposed spectrum reconfiguration approaches to re-allocate spectrum resources by solving the auxiliary graph. In [8], a push-pull technique was introduced, which smoothly shifted existing optical paths to new frequencies, instead of termination before setting up a new optical path. Fragmentation-aware RSA algorithms were discussed in [9], which used an indicator to represent spectrum fragmentation condition of each link. Besides the above schemes that directly deal with spectrum fragmentation issue, we can also make use of existing small-bandwidth spectrum resources by transmitting

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traffic through several optical paths, which gives path multipath routing schemes.

By utilizing small-size spectrum resources, multipath routing schemes, such as virtual concatenation technique, can reduce traffic blocking ratio and enhance network performance [10]. In EON, some multipath routing algorithms have been discussed [11]–[15]. In [11], authors proposed a split spectrum approach, which utilized several sub-flows in the same optical path to transmit one traffic request. In [12], authors built analytical models to evaluate the performance of different splitting ratios under static and dynamic scenarios. Authors in [13]–[15] discussed the performance improvement that could be achieved by provisioning multipath routing together with single path routing rather than provisioning single path routing only. However, due to imperfect shape of the optical filters deployed in optical network, guard bands are allocated and placed between two adjacent connections in spectrum domain to avoid interference. Moreover, when a connection is split, it needs both extra guard bands and BVTs. Especially under heavy network loads, spectrum resources are scarce and fragmented. Multipath routing may create too many small-size connections. In this condition, multipath routing no longer benefits from small-size spectrum resources but, on the contrary, degrades spectrum efficiency and the network performance due to excessive traffic splitting operations. If we can reduce the number of guard bands allocated to split connections, multipath routing scheme should significantly improve spectrum utilization because of higher flexibility of spectrum allocation than single path routing. In order to reduce guard bands, we can aggregate several connections and transmit them as one.

Traffic grooming is a technology to combine several connections into one optical path without inserting guard bands in between [16]. In EON, traffic grooming has been introduced into both static [17] and dynamic scenarios [18] to utilize spectrum resources and reduce transmitter usage. Conventional traffic grooming needs intermediate optical-electrical-optical (OEO) conversions to separate connections, which induces extra energy consumption and time delay. Recently, a novel traffic grooming scheme has been proposed in OFDM-based EON [19]. This scheme aggregates traffic connections originated from same source node and then optically separates them at intermediate nodes using bandwidth-variable wavelength-selective switches (BV-WSS) without inducing interference. As a tradeoff of eliminating OEO conversions, it needs advanced intermediate node design to realize the broadcast-and-select function. In [20], authors proposed a shared splitting node architecture to reduce the usage of BV-WSS. In the study of [21], different numbers of splitting sections were compared and results showed that even one splitting section per node could bring significant improvement of blocking probability. Fig. 1 illustrates an example of traffic grooming in OFDM-based EON. By applying traffic grooming, one guard band and one BVT can be saved as shown in Fig. 1(b), compared with that in Fig. 1(a). However, while the bandwidth of traffic request increases in EON, the bandwidth of guard band remains the same. Single path routing schemes already have relatively low the spectrum overhead, which is the ratio of bandwidth of guard band to bandwidth of data. This low spectrum overhead reduces the benefit of saving guard bands in traffic grooming. But under heavy traffic loads in multipath routing schemes, this situation is changed due to creating too many small-size connections. Thus, the spectrum overhead in multipath routing is much higher than that it in single path routing. Traffic grooming can greatly improve the spectrum utilization by reducing guard bands in multipath routing. Overall, multipath routing with traffic grooming could significantly improve the spectrum utilization and achieve much better performance than either the multipath routing algorithms without traffic grooming or those single path routing algorithms with traffic grooming.

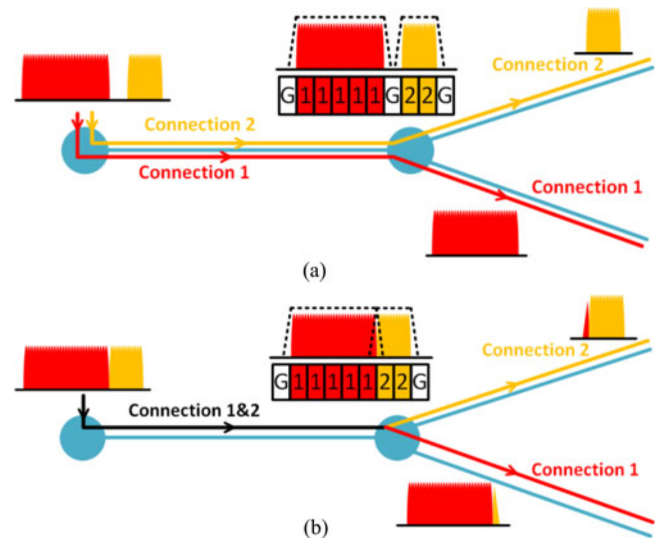

Fig. 1. Illustration of traffic grooming in OFDM-based EON. Connection 1 and Connection 2 are originated from the same source node. (a) Spectrum allocation without traffic grooming. (b) Spectrum allocation with traffic grooming.

In this paper, we propose a dynamic multipath routing algorithm with traffic grooming (MPTG) to improve the spectrum efficiency by saving guard bands and reduce the BVT usage. When a connection is split, the proposed MPTG algorithm first combines these split sub-connections with the existing optical paths before setting up new paths. The proposed MPTG algorithm inherits the advantage of reducing the bandwidth blocking ratio (BBR) as in multipath routing schemes and further enhance the performance by allocating less guard bands and using fewer BVT. Simulation results of the MPTG algorithm has been compared to both the results of multipath routing without traffic grooming and the results of single path routing with traffic grooming (SPTG). Performance metrics such as BBR, network throughput, and average BVT usage per request, are analyzed to evaluate the enhancement of the proposed MPTG algorithm.

The rest of this paper is organized as follows. Section II states the problem that we consider and illustrates the proposed MPTG algorithms. The detailed algorithm with different grooming policies is showed in section III. Section IV analysis simulation results and compares the performances of different schemes. Section V summarizes this paper.

II. Multipath Routing Traffic Grooming Algorithm

In this section, we formulate the problem of dynamic multipath routing with traffic grooming and constraints in solution design. Then an intuitive scenario is shown to illustrate spectrum allocation in MPTG algorithm.

Consider a network topology *G (V, E)*, where *V* is the node set, *E* is the undirected fiber link set. Every fiber link carries a set of indexed spectrum slots, *N*, and each spectrum slot occupies *B* GHz bandwidth. As distance-adaptive modulation format allocation is another dimension of flexibility in spectrum allocation of EON, it can benefit all schemes by densely packing spectrum resources. Thus for simplicity, we assume that uniform modulation format (e.g., BPSK) is adopted by all traffic connections and *B* GHz bandwidth can accommodate *B* Gb/s capacity. *K* shortest paths for each source-destination node pair are pre-computed for routing and P_{sd} represents the candidate routing path set for node pair *s-d*. We define that a spectrum path is formed by several contiguous spectrum slots, which are available on all fiber links along a candidate routing path. The capacity of a spectrum path is equal to the total bandwidth it consumes on each fiber link. Therefore, one candidate routing path can contain several spectrum paths, which locate at different spectrum ranges. For each arrived traffic request *R (s, d, C)*, which starts from node *s* to node *d* and requires *C* Gb/s capacity, the proposed MPTG algorithm is to assign a possible set of spectrum paths p_{sd}^{i,f_j,C_j} according to set P_{sd}, where *i* represents the *i*th candidate routing path in P_{sd}, f_j is the beginning index of *j*th spectrum path, and C_j is the assigned capacity of *j*th spectrum path.

In order to successfully accommodate the request *R(s, d, C)*, MPTG algorithm should satisfy some constraints when it selects spectrum paths. For the assigned spectrum path, the sum of their capacity should satisfy

$$C = \sum_j C_j \tag{1}$$

where C_j is the capacity of *j*th assigned spectrum path. Otherwise, this request will be blocked.

Normally, if set up new connection for *j*th spectrum path, the bandwidth b_j is

$$b_j = C_j + GB \tag{2}$$

where *GB* is the size of guard band, which is assumed to be one spectrum slot. For simplicity, we assume that guard band is inserted at the highest index of each connection.

By applying traffic grooming, MPTG algorithm can save spectrum through removing the guard bands between groomed connections over their common fiber links. As one spectrum path can have at most two neighbors in spectrum domain, it can be groomed with up to two existing connections. When spectrum path is groomed with one existing connection, one guard band can be saved over all shared fiber links. Thus, over shared fiber links, the bandwidth b_j becomes

$$b_j = C_j + GB \times \left(1 - \sum_k g_{j,k}\right)$$
$$\sum_k g_{j,k} \le 2 \tag{3}$$

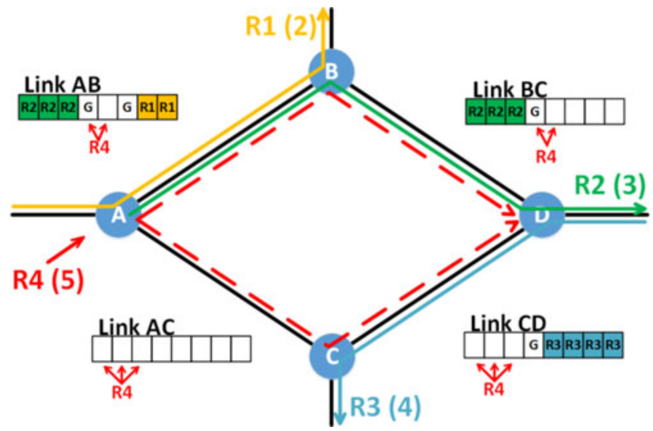

Fig. 2. MP with traffic grooming.

where $g_{j.k}$ is a binary variable that indicates whether spectrum path *j* is groomed with existing connection *k*. Then a new connection is formed, and over shared fiber links, the bandwidth of this new connection, B_j, is

$$B_j = b_j + \sum_k (g_{j,k} B_k) \tag{4}$$

where B_k is the original bandwidth of existing connection *k*. As this new connection consumes only one BVT, the bandwidth should be constrained by BVT capacity

$$B_j \le U \tag{5}$$

where *U* is the maximum bandwidth of BVT.

Fig. 2 illustrates a simple example of multipath routing with traffic grooming. Three existing optical paths (*R1*, *R2*, and *R3*) and spectrum usage of four links (*AB, BD, AC, CD*) are shown in the figure, where path *R1* bypasses Link *AB* and occupies two spectrum slots; path *R2* starts from Node *A* and traverses through Link *AB* and Link *BD*. It consumes three spectrum slots; path *R3* goes through Link *CD* and occupies four spectrum slots. A new request *R4* arrives at Node *A* to destination Node *D* and requires five spectrum slots, and the maximum bandwidth of BVT is assumed to be five spectrum slots. There are two optional paths (*A-B-D* and *A-C-D*) but neither of them has five consecutive available spectrum slots to provision single path routing. Even if we apply multipath routing, only four available spectrum slots can be allocated and then request *R4* will be blocked. By grooming with existing request *R2* through Link *AB* and Link *BD*, request *R4* can be accommodated as arrow marks shown in Fig. 2. Then request *R4* is successfully routed and consumes only one extra BVT. In this way, multipath routing with traffic grooming utilizes spectrum resources and also reduce BVT usage.

III. Dynamic RSA Algorithm

In this section, we describe the details of proposed MPTG algorithm in Algorithm 1 and explain six proposed spectrum allocation schemes.

As each connection has to occupy at least one spectrum slot for transmission, the maximum number of connections for a

Algorithm 1 MPTG Algorithm

Pre-compute and store *K* shortest paths for each *s*-*d* node pair
while network is running **do**
  When a request *R(s,d,C)* arrives, load the routing paths set P_1 for node pair *s*-*d*
  Find all existing connections, which start from node *s,* and put them into set P_2
  for each routing path *p* in P_1 **do**
    for each existing connection p' in P_2 **do**
      if *p* and p' share fiber links from node *s* and do not re-join after separation AND the transmitter of p' has spare capacity **then**
        Search along *p* and find available spectrum slots, which are adjacent to the slots occupied by p'
        if the found spectrum slots exceed the spare capacity of transmitter of p' **then**
          Keep maximum number of found spectrum slots according to the transmitter's spare capacity
        end if
        Reserve the found spectrum slots, form them into a spectrum path, and put the spectrum path into set F_1
      end if
    end for
    Find all available spectrum paths along routing path *p*
    Reserve the spectrum paths found and put them into set F_2
  end for
  Sort and allocate spectrum paths in F_1 and F_2 respectively according to specific grooming schemes
  Revert unallocated spectrum resources
  If no sufficient slots allocated, block this request
end while

single node is |*N*|. For *K* shortest paths with less than |*V*| hops, at most $|V| \times K \times |N|^2$ spectrum slot searching operations are performed. For traffic grooming spectrum allocation, the time complexity is $O(|V| \times K \times |N|^2 \times log(|V| \times K \times |N|^2))$. The time complexity of spectrum allocation in non-grooming part is $O(|V| \times K \times |N| \times log(|V| \times K \times |N|))$. Overall, the time complexity of the proposed algorithm is polynomial.

As multipath routing consumes additional guard bands and BVT, RSA algorithms proposed by others [13]–[15] all adopt hybrid routing, which considers multipath routing only if single path routing fails. By applying traffic grooming, we can utilize BVT bandwidth and reduce guard band allocation, which can alleviate the impact induced by multipath routing. Cooperating with traffic grooming, multipath routing is expected to further enhance the performance. Therefore, in this paper, we propose two routing schemes, one is hybrid routing as others, and the other is multipath-only routing, which does not firstly provision single path routing by searching the entire candidate path set. For hybrid routing, algorithm assigns spectrum paths in set F_1 and F_2 in the order of $F_1 \rightarrow F_2 \rightarrow F_1 \rightarrow F_2$, where the first round of $F_1 \rightarrow F_2$ is for searching possible single path routing. For multipath routing, algorithm takes the order of $F_1 \rightarrow F_2$. With different spectrum path sorting concerns, we have also proposed three traffic grooming policies for both hybrid and multipath-only schemes:

A. Shortest Path First (SPF)

This policy sorts spectrum paths in both set F_1 and F_2 in ascending order of path distance. It is straightforward and tries to minimize transmission latency. However, it may not be efficient when the traffic is heavy because certain fiber links may get congested.

B. Maximum Usable Bandwidth (MUB)

This policy sorts spectrum paths in both set F_1 and F_2 in descending order of usable bandwidth, in terms of the number of slots. It aims to maximize the bandwidth of sub-connections so that the number of consumed BVT is minimized. As the bandwidth of each sub-connection is increased in this policy, the spectrum ratio of the guard bands to data transmission is implicitly reduced.

C. Largest Spectrum Saving (LSS)

This policy sorts spectrum paths in set F_1 in descending order of spectrum saving ratio ***r***, which is defined as

$$r = \frac{\text{bandwidth can be saved from guard bands}}{\text{total bandwidth of this spectrum path}}.$$

As the ratio for spectrum paths in set F_2 is always zero, this policy sorts spectrum paths in set F_2 as MUB policy. It aims to maximize spectrum efficiency for each allocated path.

In general, we propose six MPTG schemes, which are MPTG-SPF, MPTG-MUB, and MPTG-LSS for hybrid routing, MPTG-SPF-M, MPTG-MUB-M, and MPTG-LSS-M for multipath-only routing.

IV. Performance Evaluation

Numerical simulations have been perform to evaluate the performance of the proposed MPTG schemes and compare them to that of the two benchmarks, which are multipath provisioning (MP) without traffic grooming and SPTG. MP algorithm is referred from [14] using *K*-shortest paths routing, first-fit RSA algorithm. SPTG algorithm is similar to the FPA algorithm in [20] but using *K*-shortest paths instead of disjoint shortest paths. *K*-shortest paths are computed using Yen's algorithm [22].

A. Assumptions and Parameters

We studied the proposed MPTG algorithms in two network topologies with different network connectivity (see Fig. 3), namely the 14-node 22-link NSFNET network (see Fig. 3(a)), and the 24-node 43-link USNET network (see Fig. 3(b)). We assume that all nodes in the networks are capable of both traffic

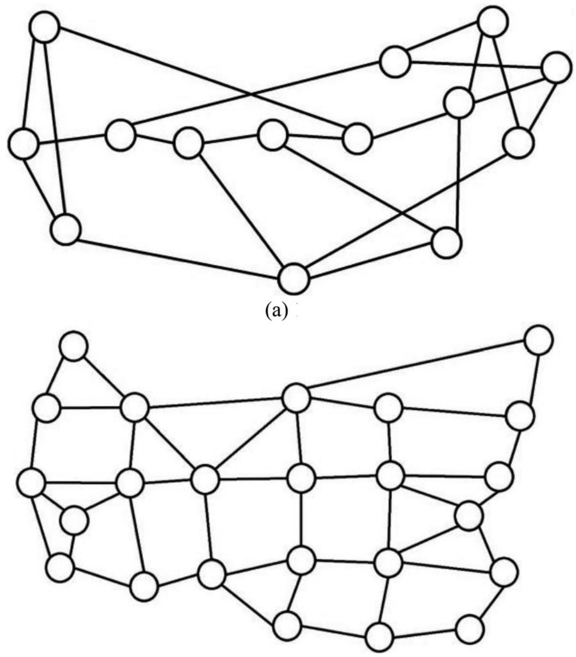

Fig. 3. Network topologies considered for simulation. (a) 14-node 22-link NSFNET. (b) 24-node 43-link USNET.

TABLE I
SIMULATION PARAMETERS

Spectrum management grid	12.5 GHz
Number of spectrum slot on each fiber link	320
Number of pre-computed path (K)	5
Guard band size	12.5 GHz
Maximum bandwidth of BVT	200 GHz
Data rate of each request	12.5–200 Gb/s

grooming and broadcast-and-select function to optically separate connections. Single fiber link is assumed to connect two neighboring nodes for data transmission in both directions. It is also assumed that each node is equipped with enough number of BVT so that request blocking happens only if spectrum resources are not enough. All traffic requests arrive one by one in a Poisson process with parameter λ and their respective durations satisfy negative exponential distribution with parameter μ. Hence, the traffic load is calculated as λ/μ *Erlang*. Source and destination nodes of each request are randomly generated among all node pairs in the network. The modulation format in every connection is assumed to be the same and the connection requires the same amount of bandwidth as its bit-rate (say 100 Gb/s requires 100 GHz bandwidth). Differential delay is not considered, as the maximum differential delay is bounded by K shortest path. In this study, the value of K is a small so that differential delay issue can be resolved by deploying electrical buffer at the receiver end. Parameters applied in simulation are listed in Table I.

We have evaluated the performance metrics such as BBR, network throughput, and average BVT usage per request, where BBR is defined as the ratio of blocked bandwidth to total required bandwidth and network throughput is defined as traffic

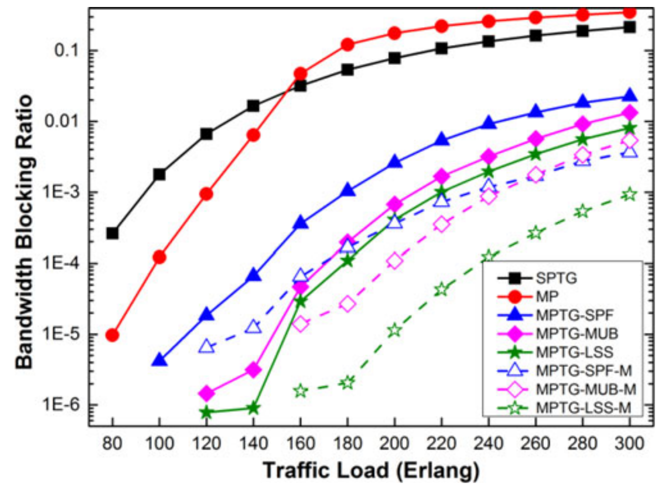

Fig. 4. BBR versus traffic load (NSFNET).

volume of entire network. For average BVT usage, we only calculate the extra consumed BVT by requests, which means that if all sub-connections of a request can be groomed to existing connections, it takes zero BVT in statistics.

B. NSFNET

Fig. 4 shows BBR over different traffic loads. BBR of all algorithms increases when the traffic loads increase. Single path routing algorithm results in a higher BBR than multipath routing schemes when the traffic load is light, as the multipath schemes utilize small-size spectrum slots by splitting large bandwidth request into smaller size sub-connections. As expected, when the traffic load is heavy, MP algorithm gets higher BBR because it splits requests into too many small-size sub-connections. By applying traffic grooming to reduce guard band allocation and improve spectrum efficiency, six proposed MPTG schemes all outperform SPTG and MP algorithms. Three proposed multipath-only routing schemes (MPTG-SPF-M, MPTG-MUB-M, and MPTG-LSS-M) achieve lower BBR than the three hybrid routing schemes (MPTG-SPF, MPTG-MUB, MPTG-LSS). It shows that traffic grooming can enhance performance when connections are of relatively small size. For three grooming policies, MUB gets lower BBR than SPF, as MUB implicitly improves spectrum efficiency by utilizing BVT bandwidth. LSS policy achieves the lowest BBR because it tries to allocate less guard bands to improve the spectrum efficiency. In all simulated algorithms, MPTG-LSS-M achieves the lowest BBR.

Fig. 5 shows the network throughput over different traffic loads. When traffic load is light, the BBR of each algorithm is relatively low and the network throughput is linearly increasing as the traffic load. When the traffic is getting heavy, both MP and SPTG algorithms exhibit reduced increasing rates in their network throughputs, which are actually degraded by their relatively higher BBR. Nevertheless, all six proposed MPTG schemes achieve higher network throughput than the SPTG and MP algorithms, due to their relatively lower BBR.

Fig. 6 shows average BVT usage of every request over different traffic loads. BVT usage in the MP algorithm sharply increases when traffic load is heavy, as the MP algorithm splits

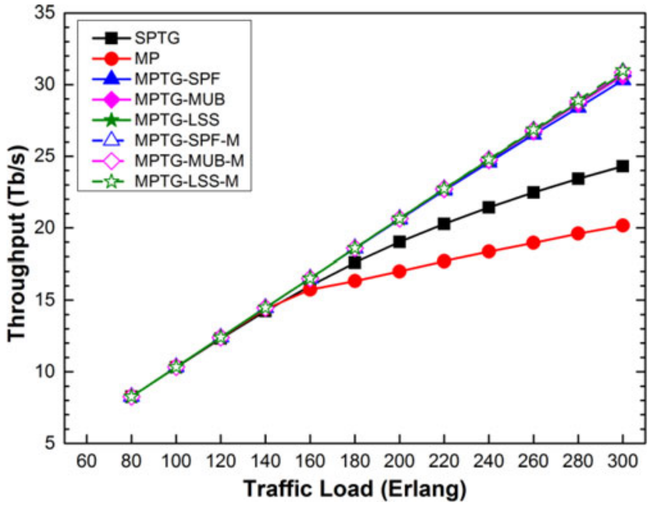

Fig. 5. Network throughput versus traffic Load (NSFNET).

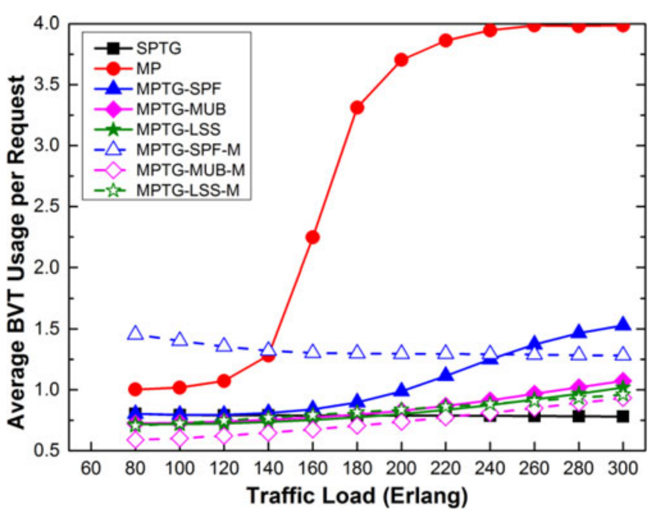

Fig. 6. Average BVT usage per request versus traffic load (NSFNET).

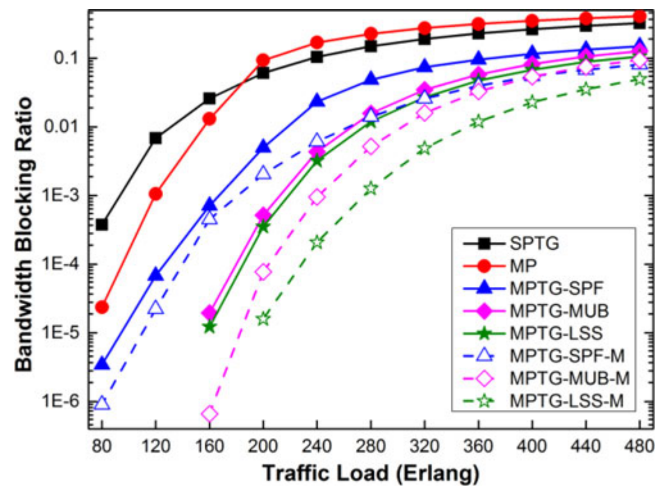

Fig. 7. BBR versus traffic load (USNET).

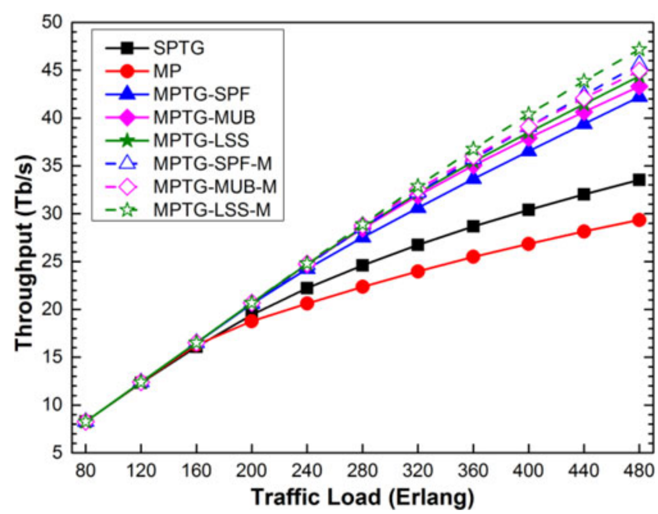

Fig. 8. Network throughput versus traffic load (USNET).

request into too many sub-connections. BVT usage of SPTG is slightly less than one because BVT usage of the single routing scheme is at most one and traffic grooming further reduces this number. Among the six proposed schemes, MPTG-SPF and MPTG-SPF-M schemes result in relatively higher BVT usage, as the SPF fit allocation makes every shortest path between each node pair very congested, so that requests have to be split to many sub-connections and occupy more BVT. MPTG-SPF-M consumes the largest number of BVT, as it tries to assign traffic all through the shortest path, regardless of the spectrum usage and split them into more sub-connections than MPTG-SPF. All of MPTG-LSS, MPTG-LSS-M, MPTG-MUB and MPTG-MUB-M consume relatively average BVT usage, as compared with the SPTG algorithm, which shows that traffic grooming effectively reduces BVT usage. It is further noticed that when the traffic load is not too high, the average BVT usage of MPTG-LSS-M and MPTG-MUB-M are even less than that of SPTG. In all simulated algorithms, MPTG-MUB-M achieves the lowest average BVT usage.

C. USNET

USNET network topology has also been considered to investigate the performance of proposed traffic grooming schemes in a larger network. Simulation results of BBR (see Fig. 7), network throughput (see Fig. 8), and average BVT usage (see Fig. 9) follow the similar trend of results as in NSFNET. So regardless of the network topology, the proposed algorithms achieve similar performance improvements. The improvement of MPTG algorithms in USNET is less than that in NSFNET, due to the relatively less choice of path selection, as the network connectivity is larger while the number of pre-computed paths (K) remains the same.

V. SUMMARY

In this paper, we proposed a traffic groomed multipath routing algorithm for EON. By splitting the traffic request into multiple small-size sub-connections for separate transmission and combining small-size connections originated from the same source node to share common fiber links, the proposed

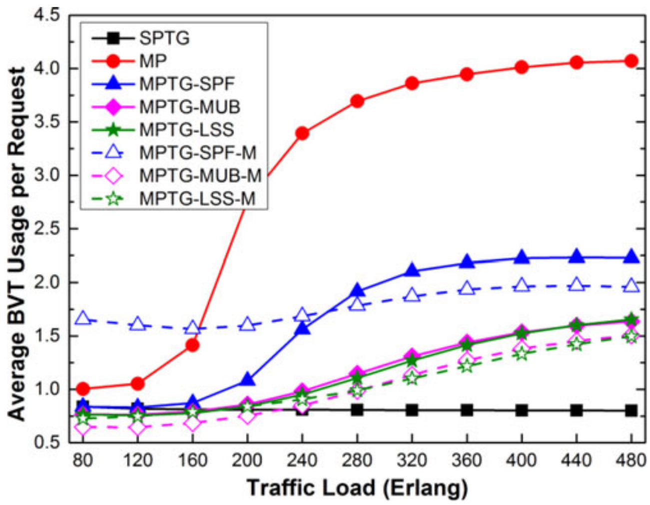

Fig. 9. Average BVT usage per request versus traffic load (USNET).

algorithm (MPTG) not only inherit the flexibly spectrum allocation from multipath routing, but also save the spectrum assigned to guard-band and the BVTs used by different connections. Six different schemes employing the proposed algorithm have been investigated and characterized, via simulations. The results show that the proposed MPTG algorithm effectively reduces BBR and enhances network throughput compared with the previously reported multipath routing or single path routing algorithms.

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, no. 11, pp. 66–73, Nov. 2009.

[2] O. Gerstel, M. Jinno, A. Lord, and S. Yoo, “Elastic optical networking: A new dawn for the optical layer?” *IEEE Commun. Mag.*, vol. 50, no. 2, pp. s12–s20, Feb. 2012.

[3] J. Armstrong, “OFDM for optical communications,” *J. Lightw. Technol.*, vol. 27, no. 3, pp. 189–204, Feb. 2009.

[4] W. Zheng, Y. Jin, W. Sun, W. Guo, and W. Hu, “On the spectrum efficiency of bandwidth-variable optical OFDM transport networks,” in *Proc. Nat. Fiber Opt. Eng. Conf., Opt. Fiber Commun. Conf. Expo.*, Mar. 2010, pp. 1–3.

[5] K. Christodoulopoulos, I. Tomkos, and E. Varvarigos, “Elastic bandwidth allocation in flexible OFDM-based optical networks,” *J. Lightw. Technol.*, vol. 29, no. 9, pp. 1354–1366, May 2011.

[6] Y. Wang, X. Cao, and Y. Pan, “A study of the routing and spectrum allocation in spectrum-sliced elastic optical path networks,” in *Proc. IEEE Conf. Comput. Commun.*, Apr. 2011, pp. 1503–1511.

[7] Y. Yin, K. Wen, D. Geisler, R. Liu, and S. J. B. Yoo, “Dynamic on-demand defragmentation in flexible bandwidth elastic optical networks,” *Opt. Exp.*, vol. 20, no. 2, pp. 1798–1804, 2012.

[8] F. Cugini, F. Paolucci, G. Meloni, G. Berrettini, M. Secondini, F. Fresi, N. Sambo, L. Poti, and P. Castoldi, “Push-pull defragmentation without traffic disruption in flexible grid optical networks,” *J. Lightw. Technol.*, vol. 31, no. 1, pp. 125–133, Jan. 2013.

[9] X. Wang, Q. Zhang, I. Kim, P. Palacharla, and M. Sekiya, “Utilization entropy for assessing resource fragmentation in optical networks,” in *Proc. Nat. Fiber Opt. Eng. Conf., Opt. Fiber Commun. Conf. Expo.*, Mar. 2012, pp. 1–3.

[10] G. Shen, A. Cai, and L. Peng, “Benefits of sub-band virtual concatenation (VCAT) in CO-OFDM optical networks,” in *Proc. 14th Int. Conf. Transp. Opt. Netw.*, Jul. 2012, pp. 1–4.

[11] S. Dahlfort, M. Xia, R. Proietti, and S. Yoo, “Split spectrum approach to elastic optical networking,” in *Proc. 38th Eur. Conf. Exhib. Opt. Commun.*, Sep. 2012, pp. 1–3.

[12] A. Cai, L. Peng, and G. Shen, “Subband virtual concatenation lightpath blocking performance evaluation for CO-OFDM optical networks,” in *Proc. Asia Commun. Photon. Conf.*, Nov. 2012, pp. 1–3.

[13] A. Pages, J. Perello, and S. Spadaro, “Lightpath fragmentation for efficient spectrum utilization in dynamic elastic optical networks,” in *Proc. 16th Int. Conf. Opt. Netw. Des. Model.*, Apr. 2012, pp. 1–6.

[14] X. Chen, A. Jukan, and A. Gumaste, “Multipath de-fragmentation: Achieving better spectral efficiency in elastic optical path networks,” in *Proc. IEEE Conf. Comput. Commun.*, Apr. 2013, pp. 390–394.

[15] 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, no. 1, pp. 15–22, Jan. 2013.

[16] K. Zhu and B. Mukherjee, “Traffic grooming in an optical WDM mesh network,” *IEEE J. Sel. Areas Commun.*, vol. 20, no. 1, pp. 122–133, Jan. 2002.

[17] Y. Zhang, X. Zheng, Q. Li, N. Hua, Y. Li, and H. Zhang, “Traffic grooming in spectrum-elastic optical path networks,” in *Proc. Nat. Fiber Opt. Eng. Conf., Opt. Fiber Commun. Conf. Expo.*, Mar. 2011, pp. 1–3.

[18] S. Zhang, C. Martel, and B. Mukherjee, “Dynamic traffic grooming in elastic optical networks,” *IEEE J. Sel. Areas Commun.*, vol. 31, no. 1, pp. 4–12, Jan. 2013.

[19] G. Zhang, M. De Leenheer, and B. Mukherjee, “Optical traffic grooming in OFDM-based elastic optical networks [invited],” *IEEE/OSA J. Opt. Commun. Netw.*, vol. 4, no. 11, pp. B17–B25, Nov. 2012.

[20] P. S. Khodashenas, J. Comellas, S. Spadaro, and J. Perell, “Dynamic source aggregation of subwavelength connections in elastic optical networks,” *Photon. Netw. Commun.*, vol. 26, nos. 2/3, pp. 131–139, 2013.

[21] P. S. Khodashenas, J. Comellas, J. Perello, S. Spadaro, and G. Junyent, “On the performance of dynamic source aggregation of sub-wavelength connections in eons,” in *Proc. 16th Int. Conf. Transp. Opt. Netw.*, Jul. 2014, pp. 1–4.

[22] J. Y. Yen, “Finding the k shortest loopless paths in a network,” *Manag. Sci.*, vol. 17, no. 11, pp. 712–716, 1971.

Authors’ biographies not available at the time of publication.