Dynamic Service Provisioning in Elastic Optical Networks With Hybrid Single-/Multi-Path Routing

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***Abstract*—Empowered by the optical orthogonal frequency-division multiplexing (O-OFDM) technology, flexible online service provisioning can be realized with dynamic routing, modulation, and spectrum assignment (RMSA). In this paper, we propose several online service provisioning algorithms that incorporate dynamic RMSA with a hybrid single-/multi-path routing (HSMR) scheme. We investigate two types of HSMR schemes, namely HSMR using online path computation (HSMR-OPC) and HSMR using fixed path sets (HSMR-FPS). Moreover, for HSMR-FPS, we analyze several path selection policies to optimize the design. We evaluate the proposed algorithms with numerical simulations using a Poisson traffic model and two mesh network topologies. The simulation results have demonstrated that the proposed HSMR schemes can effectively reduce the bandwidth blocking probability (BBP) of dynamic RMSA, as compared to two benchmark algorithms that use single-path routing and split spectrum. Our simulation results suggest that HSMR-OPC can achieve the lowest BBP among all HSMR schemes. This is attributed to the fact that HSMR-OPC optimizes routing paths for each request on the fly with considerations of both bandwidth utilizations and lengths of links. Our simulation results also indicate that the HSMR-FPS scheme that use the largest slots-over-square-of-hops first path-selection policy obtains the lowest BBP among all HSMR-FPS schemes. We then investigate the proposed algorithms' impacts on other network performance metrics, including network throughput and network bandwidth fragmentation ratio. To the best of our knowledge, this is the first attempt to consider dynamic RMSA based on both online path computation and offline path computation with various path selection policies for multipath provisioning in O-OFDM networks.**

***Index Terms*—Bandwidth blocking probability (BBP), bandwidth fragmentation ratio, dynamic routing, elastic optical networks, hybrid single-/multi-path routing (HSMR), modulation and spectrum assignment (RSA).**

I. Introduction

OVER the past decade, Internet traffic has been growing at an annual rate of more than 30%, and the consequent bandwidth (BW) demands stimulated research and development for highly flexible and scalable networking technologies. Recent research advance has experimentally demonstrated transmission of 20 Tb/s signals on a single fiber with the dense wavelength division multiplexing (DWDM) technology [1]. However, due to the coarse granularity of DWDM channels (typically at 50 or 100 GHz), wavelength-routed DWDM network infrastructure [2] has been considered rigid with limited elasticity and flexibility in the optical layer. When the support of highly dynamic traffic becomes necessary, repeated optical-to-electrical-to-optical (O/E/O) conversions are required to forward the data to electrical routers for packet switching. These O/E/O conversions usually incur additional capital expenditures (CAPEX) and operational expenditures (OPEX) owing to relatively high equipment cost and power consumption [3]. To this end, it is highly desirable to develop networking technology that provides subwavelength granularity in the optical layer.

A. *Optical Orthogonal Frequency-Division Multiplexing (O-OFDM)-Based Elastic Optical Networks*

The O-OFDM technology [4], [5] packs subcarrier frequency slots overlapping with each other in the optical spectrum. Since the subcarriers are orthogonal in the frequency domain, data modulation on them can be recovered without interference at the receiver [5]. Hence, O-OFDM can achieve subwavelength granularity, by using elastic BW allocation that manipulates the subcarrier slots. Specifically, a BW-variable O-OFDM transponder can assign an appropriate number of subcarrier slots to serve a lightpath request using just-enough BW [6]. Moreover, the modulation level of the subcarrier slots can be adaptive to accommodate various quality of transmission [7], [8]. The elastic nature of O-OFDM imposes sophisticated network planning and provisioning procedures for efficient and robust operations. To address these, we need to develop routing, modulation-level, and spectrum assignment (RMSA) algorithms for network control and management. If modulation level is not adaptive in the networks, RMSA reduces to routing and spectrum assignment (RSA).

Planning and provisioning of elastic O-OFDM networks have started to attract research interests just recently [9]–[15]. When the lightpath requests are known *a prior*, offline planning of O-OFDM networks with RSA/RMSA under the spectrum-continuity constraints is known as nonpolynomial complete [9]. An RSA heuristic that combined shortest path routing and first-fit spectrum assignment was discussed in [10]. In [9], several integer linear programming (ILP) models were formulated and solved for offline RMSA, and a heuristic based on shortest path routing and simulated annealing optimization was proposed to reduce the computation complexity. Jinno *et al.* [11] proposed a BW-efficient RMSA, which examined K-shortest routing paths

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for each request and then chose the one with the lowest available contiguous slots. Wang *et al.* [12] formulated an ILP model for offline RSA and designed two heuristics, K-shortest path routing and balanced-load spectrum assignments and shortest path routing and maximum spectrum reuse assignments. Online provisioning of O-OFDM networks considers how to serve time-variant lightpath requests with dynamic RSA/RMSA. By leveraging the generalized multiprotocol label switching signaling mechanism, a distributed dynamic RMSA was proposed in [13], which chose the least congested routing path and performed first-fit spectrum assignments. Sone *et al.* [14] developed a dynamic RSA that used a metric to quantify the consecutiveness of available slots among relevant fibers. The investigation in [15] considered spectrum defragmentation during online provisioning with dynamic RSA.

B. Service Provisioning With Multipath Routing

From the aforementioned discussion, we can see that most of the previous works on O-OFDM networks were based on single-path routing. However, for online provisioning, we may have difficulty to serve certain large-BW requests with single-path routing due to the BW limitation, thus resulting in high request blocking probability [16]. It is known that multipath routing provides increased throughput and utilizes the network resources more efficiently [2], [16]. Researchers have previously considered to include multipath routing support in SONET/SDH transport systems [17]–[19]. Multipath routing is also explicitly supported by several standardized routing protocols, such as the open shortest path first [20] and the routing information protocol [21].

What is more promising is that with the elastic nature of O-OFDM, network nodes can easily split data traffic over multiple routing paths and support multipath provisioning. Recently, Dahlfort *et al.* proposed a split-spectrum approach [22], which could be considered as a multipath approach as a request might be divided into several subflows for transmitting on noncontiguous optical spectra. However, since this approach still restricted all subflows of a request to be routed over the same path, it may not fully explore the benefits of multipath provisioning. In order to support multipath routing and traffic-splitting in O-OFDM networks, each switching node requires a wavelength-selective switch (WSS) that can add/drop subcarrier channels using relatively low BW granularity. Thanks to the technology advances in liquid crystal-on-silicon (LCOS) WSS, switching granularity at 12.5 GHz can be realized [23]. Barros *et al.* proposed a colorless LCOS WSS node architecture in which each add/drop port had both narrow-band and wide-band modes [24]. Hence, BW-flexible switching could be achieved with low loss. Such WSS provides an important enabling technology for supporting multipath routing in O-OFDM networks.

C. Our Contributions

In this paper, we propose several dynamic service provisioning algorithms that incorporate a hybrid single-/multi-path routing (HSMR) scheme. To the best of our knowledge, this is the first attempt to consider dynamic RMSA based on both online path computation and offline path computation with various path selection policies for multipath provisioning in O-OFDM networks. We evaluate the proposed algorithms with numerical simulations using a Poisson traffic model. The simulation results have demonstrated that the proposed HSMR schemes can effectively reduce the bandwidth blocking probability (BBP) of dynamic RMSA, as compared to two benchmark algorithms that use single-path routing or split spectrum. We also evaluate our proposed algorithms in terms of other performance metrics, such as network throughput and network BW fragmentation ratio. Notice that for multipath provisioning, the differential delay between the routing paths can lead to the requirement for additional buffers on the end nodes [25]. How to address the differential delay during multipath provisioning is out of the scope of this paper. We expect that the issue can be resolved with either the split-spectrum approach that restricts all subflows of a request to be routed over the same path [22] or a multipath provisioning approach that considers the differential delay constraint.

The rest of this paper is organized as follows. Section II formulates the problem of service provisioning using dynamic RMSA with HSMR. The dynamic RMSA algorithm that incorporates HSMR with online path computation is discussed in Section III. Section IV explains the dynamic RMSA with HSMR using fixed path sets. The numerical simulation setup and results for performance evaluation are discussed in Section V. Finally, Section VI summarizes the paper.

II. Service Provisioning Using Dynamic RMSA With HSMR

In this section, we formulate the problem of service provisioning using dynamic RMSA with HSMR, explain operation constraints, and define design metrics.

Consider the physical network topology $G(V, E, B, D)$, where V is the node set, E is the fiber link set, each fiber link can accommodate B frequency slots at most, and D represents the lengths of $e \in E$. We assume that the BW of each subcarrier slot is unique as BW_{slot} GHz. The capacity of a slot is $M \cdot C_{\text{slot}}$, where M is the modulation level in terms of bits per symbol, and C_{slot} denotes the capacity of a slot when the modulation is BPSK ($M = 1$) and is a function of BW_{slot} [9]. In this study, we assume that M can be 1, 2, 3, and 4 for BPSK, QPSK, eight quadrature-amplitude modulation (8-QAM), and 16-QAM, respectively. For a lightpath request $\text{LR}(s, d, C)$ from node s destined to d for a capacity of C, the provisioning algorithm using dynamic RMSA with the HSMR scheme needs to determine a set of routing paths $\{R_{s,d,i}\}$ to serve the request, where i is the index of each routing path. Note that for different i, the routing paths $R_{s,d,i}$ can be identical, but since their spectrum allocations are not contiguous, more than one sets of O-OFDM transceivers are required and this scheme is considered as a multipath one. In this study, we propose two algorithms to determine $\{R_{s,d,i}\}$ for each request, i.e., one with online path computation and the other with fixed path sets. The details of the algorithms will be discussed in Sections III and IV.

We denote the length of a link $e \in E$ as d_e, $d_e \in D$. When the transmission distance of the ith routing path $R_{s,d,i}$ is known, we derive the modulation level M_i as

$$M_i = mlvl\left(\sum_e d_e\right), e \in R_{s,d,i} \tag{1}$$

where $mlvl(\cdot)$ returns the highest modulation level that a transmission distance can support. Specifically, we assume that each modulation M can support a maximum transmission distance based on the receiver sensitivities [7], and when the distance of $R_{s,d,i}$ permits, we always assign the highest modulation level to guarantee high spectral efficiency.

Then, we figure out the load distribution $\{C_i\}$ on each routing path based on the network status, which should satisfy

$$C = \sum_i C_i. \tag{2}$$

The number of contiguous slots N_i we need to assign on each path is

$$N_i = \left\lceil \frac{C_i}{M_i \cdot C_{\text{slot}}} \right\rceil + N_{\text{GB}} \tag{3}$$

where N_{GB} is the number of slots for the guard band. Note that when splitting the traffic, we have to take the cost that more slots will be used for the guard band. In the context of this study, we assume that $N_{\text{GB}} = 1$ and this guard band is inserted as the highest indexed slot in the spectrum assignment of each connection. Therefore, in the following sections, we do not mention the guard band explicitly, but when we refer to the size of a block of contiguous available slots, we actually mean the available size after deducting the guard band.

The last step of dynamic RMSA is the spectrum assignment to finalize the allocations of contiguous slots along the fiber links on $R_{s,d,i}$. We assume that there is not any spectrum converter in the network. For each fiber link $e \in E$, we define a bit-mask b_e consisting of B bits. When the jth slot on e is taken, $b_e[j] = 1$; otherwise, $b_e[j] = 0$. When assigning the frequency slots, we define a bit-mask a_i for each path, which also contains B bits. Then, the spectrum assignment on $R_{s,d,i}$ becomes the problem of finding N_i contiguous bits in a_i to turn on based on all current $b_e, e \in R_{s,d,i}$. Finally, the RMSA with HSMR for $LR(s,d,C)$ is $\{\{R_{s,d,i}, M_i, a_i\}, i = 1, \ldots\}$. We say LR is blocked, if we cannot find a feasible $\{\{R_{s,d,i}, M_i, a_i\}, i = 1, \ldots\}$ for it.

The dynamic RMSA has to satisfy the spectrum nonoverlapping and spectrum contiguousness.

Spectrum Nonoverlapping Constraint:

$$\text{sum}(a_i \cap b_e) = 0, \quad \forall e \in R_{s,d,i}. \tag{4}$$

Spectrum Contiguousness Constraint:

$$\text{sum}(a_i \cap ROR(a_i, 1)) = \begin{cases} N_i - 1, & N_i < B \\ B, & N_i = B \end{cases} \tag{5}$$

where $\text{sum}(\cdot)$ is the function to add all bits in a bit mask together, $\cap$ is the bitwise AND operator, and $ROR(\cdot)$ is the circular bit-right-shift operator. In this study, the objective of the service provisioning is to minimize requests' BBP.

Definition 1 (Slot block):: We define a slot block as a block of contiguous subcarrier slots in the optical spectrum.

Definition 2 (BW allocation granularity):: To avoid a request LR from being split over too many paths, we define a BW allocation granularity as g slots. Specifically, when LR is provisioned over more than one routing paths, the minimum size of the slot blocks we can allocate on each path is g. Note that increasing g discourages multipath provisioning schemes, and will eventually lead to a single-path-only scenario when g is comparable to the largest size of the requests. From the viewpoint of a BW-flexible WSS [24], g can be the smallest switching granularity that it can handle. From the viewpoint of network management, g can correspond to the smallest switching granularity that the network operator is willing to offer.

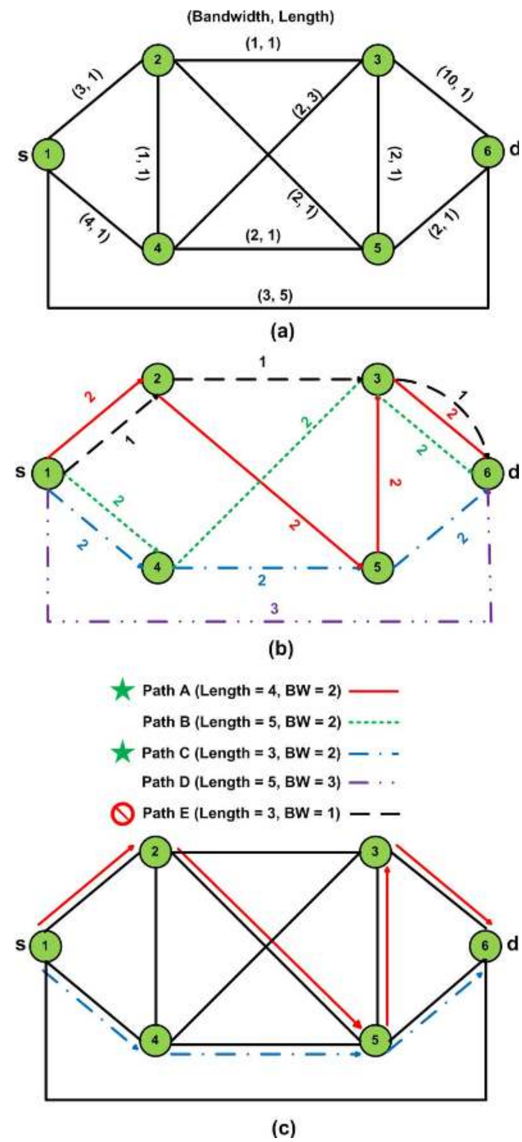

Fig. 1. Example of service provisioning using multipath routing with a BW allocation granularity of $g = 2$. (a) Network topology G(V,E,B,D). (b) Path computation results. (c) Elastic multipath provisioning scheme for a request with $\text{BW} = 4$ and $g = 2$.

Fig. 1 illustrates an intuitive example of the usage of BW allocation granularity g in service provisioning with HSMR. Fig. 1(a) shows a network topology with six nodes, and we label each link with (BW and length), i.e., its available BW in terms of the number of slots and its link length. For simplicity, we assume that each link only has one slot block available. With this $G(V,E,B,D)$, we will not be able to serve a request from node 1 to 6 for a BW of four contiguous slots with a single routing path. Hence, we calculate multiple routing paths and label them with the sizes of available slot blocks, as shown in Fig. 1(b). It is clear that Path E: 1-2-3-6 is not a qualified path for a BW allocation granularity $g = 2$ because it only has a slot block of one slot available. We select Paths A and C for less lengths and provision the request for a BW of four slots from node 1 to 6 successfully [as shown in Fig. 1(c)].

Definition 3 (Bandwidth blocking probability):: BBP is defined as the ratio of blocked connection BW versus total request BW. BBP is a commonly used metric for assessing the performance of service provisioning algorithms.

Definition 4 (BW fragmentation ratio): BW fragmentation is another interesting factor to investigate in dynamic RMSA [15]. BW fragmentation, which is similar to the file system fragmentation in computer storage, usually refers to the existing of non-aligned, isolated and small-sized slot blocks in the spectrum of elastic optical networks. Since these slot blocks are neither contiguous in the spectral domain nor aligned along fiber links, it is hard for the network operator to get them utilized for future connection requests, especially for those going across multiple hops and/or requesting for large BW. Inspired by the fragmentation ratio definition for computer storage [26], we define the BW fragmentation ratio of a link e as

$$\eta_e = \begin{cases} 1 - \frac{\mathrm{Max\,Block}(b_e)}{B - \mathrm{sum}(b_e)}, & \mathrm{sum}(b_e) < B \\ 0, & \mathrm{sum}(b_e) = B \end{cases} \tag{6}$$

where $\mathrm{Max\,Block}(\cdot)$ returns the maximum size of available slot blocks in b_e. In light of previous works on network BW fragmentation in elastic optical networks [27], [28], the fragmentation ratio F_η of the network G is defined as the average of link fragmentation ratio

$$F_\eta = \frac{\sum_e \eta_e}{|E|}. \tag{7}$$

III. Dynamic RMSA With HSMR Using Online Path Computation

We first investigate a dynamic RMSA-HSMR algorithm that considers link spectrum usage on the fly with an online path computation. Specifically, we convert $G(V, E, B, D)$ to a virtual topology $G'(V, E, D')$ based on link spectrum usage, where V and E are the same as those in G, but each link weight d'_e in set D' is recalculated as

$$d'_e = \begin{cases} +\infty, & \mathrm{Max\,Block}(b_e) < g \\ w_e \cdot \frac{sum(b_e)+g}{B}, & \mathrm{Max\,Block}(b_e) \geq g \end{cases} \tag{8}$$

where g is the BW allocation granularity, $\mathrm{sum}(b_e)$ returns the current spectrum usage of link e, and w_e is calculated from d_e with

$$w_e = M_{\max} - mlvl(d_e) + 1 \tag{9}$$

where $M_{\max}$ is the highest modulation level that can be supported in the network, and $mlvl(\cdot)$ is defined in (1) to return the highest modulation level that a transmission distance can support. Since a higher modulation means a less number of slots to allocate and better utilization of network spectrum resource, we quantify d_e with $mlvl(d_e)$ and map it to w_e to assist routing path calculation in the virtual topology. A link e is omitted from the online path computation, if it does not have a block of available contiguous slots with the size $\geq g$. Otherwise, the link weight d'_e is proportional to the product of w_e and the number of used slots $\mathrm{sum}(b_e)$. *Algorithm 1* shows the detailed procedure in implementing the proposed algorithm, and we calculate the routing path set for the path selection of each request using network status on the fly.

Algorithm 1 Dynamic RMSA With HSMR Using Online Path Computation

collect link status of $G(V, E, B, D)$;
while the network is operational **do**
  restore network resources used by expired requests;
  update link weights $\{d'_e\}$ based on the current network status, using (8)–(9);
  construct virtual topology $G'(V, E, D')$ with $\{d'_e\}$;
  get parameters of an incoming request $LR(s, d, C)$;
  calculate K-shortest routing paths from s to d in $G'(V, E, D')$;
  sort the paths based on the weighted total distances $\sum_e d'_e$;
  for all paths in the ascending order **do**
    determine the highest modulation level M_i for the path with its real distance $\sum_e d_e$ using (1);
    for all available slot blocks with sizes $\geq g$ **do**
      allocate capacity C_i to slot blocks with (3);
      if $\sum_i C_i = C$ **then**
        break inner and outer for-loops;
      end if
    end for
  end for
  if $\sum_i C_i < C$ **then**
    revert all the spectrum allocations;
    mark the request as blocked;
  end if
end while

IV. Dynamic RMSA With HSMR Using Fixed Path Sets

The major drawback of online path computation is the high computation complexity, as we need to reconstruct the virtual topology G' for each request and to perform path computation on the fly. Dynamic RMSA with HSMR can also be realized using fixed path sets, where the path-set containing K-shortest routing paths for each s--d pair in G are precomputed before operating the network. Hence, the overhead from path computation can be effectively reduced. *Algorithm 2* shows the detailed procedure in implementing the proposed algorithm. In provisioning a lightpath request $\mathrm{LR}(s, d, C)$, we sort the paths in the path set of s--d based on a path-selection policy and then process the paths one by one. We will elaborate on the details of the path-selection policies in the following. In performing spectrum allocations for C, we prefer a single routing path in a best effort scenario. Specifically, the largest slot block in the top-ranked path is selected first, and only if the largest slot block in the top-ranked path cannot support C in full, a multipath scheme is applied.

We evaluate the following path-selection policies:

a) *Shortest path first (SPF):* We select the routing path candidates in the ascending order based on the total transmission distance of the routing path, $\sum_e d_e, e \in R_{s,d,i}$.

b) *Most slots first (MSF):* We select the paths in the descending order based on the total available slots on each of them. The number of available slots on a path is

$$\mathrm{bw}(R_{s,d,i}) = B - \mathrm{sum}\left(\bigcup_{e \in R_{s,d,i}} b_e\right). \quad (10)$$

c) *Largest slots-over-hops first (LSoHF):* We select the paths in the descending order based on the metric

$$\mathrm{soh}(R_{s,d,i}) = \frac{\mathrm{bw}(R_{s,d,i})}{\mathrm{hop}(R_{s,d,i})} \quad (11)$$

where $\mathrm{hop}(R_{s,d,i})$ returns the number of hops of $R_{s,d,i}$.

d) *Largest slots-over-square-of-hops first (LSoSHF):* We order the paths in the descending order based on the metric

$$\mathrm{sosh}(R_{s,d,i}) = \frac{\mathrm{bw}(R_{s,d,i})}{\sqrt{\mathrm{hop}(R_{s,d,i})}}. \quad (12)$$

e) *Most left slots first (MLSF):* We order the paths in the descending order based on the metric

$$ls(R_{s,d,i}) = \mathrm{bw}(R_{s,d,i}) - mlvl(R_{s,d,i}) \quad (13)$$

where $mlvl(R_{s,d,i})$ returns the number of contiguous slot a capacity C uses on $R_{s,d,i}$ with the highest possible modulation-level M_i according to (3). Note that $ls(R_{s,d,i})$ can return a negative value.

Algorithm 2 Dynamic RMSA With HSMR Using Fixed Path Sets

Phase 1: Routing path precomputation by a K-shortest path algorithm

collect link status of $G(V, E, B, D)$;
for all s-d pairs in $G, s, d \in V$ **do**
  calculate K-shortest routing paths;
  record the paths;
end for

Phase 2: Dynamic RMSA provisioning with HSMR

while the network is operational **do**
  restore network resources used by expired requests;
  get parameters of an incoming request $LR(s, d, C)$;
  load the pre-computed routing paths from s to d;
  sort the paths based on a path-selection policy;
  for all paths in the sorted order **do**
    determine the highest modulation level M_i for the path with its distance using (1);
    for all available slot-blocks with sizes $\geq g$ **do**
      allocate capacity C_i to slot-blocks with (3);
      if $\sum_i C_i = C$ **then**
        break inner and outer for-loops;
      end if
    end for
  end for
  if $\sum_i C_i < C$ **then**
    revert all the spectrum allocations;
    mark the request as blocked;
  end if
end while

V. Performance Evaluation

In this section, we discuss simulation results and evaluate the performance of the proposed algorithms for RMSA with HSMR. Fig. 2 shows the network topologies, NSFNET, and US Backbone, which we used in simulations for performance evaluation of the proposed service provisioning algorithms. The lightpath requests, $\mathrm{LR}(s, d, C, \Delta t)$, arrive one by one, following a Poisson process with an average arrival rate of λ requests per time-unit, and the lifetime Δt of each request follows the negative exponential distribution with an average of $1/\mu$ time units. Hence, the traffic load can be quantified with λ/μ in Erlangs. The s--d pair of each request $\mathrm{LR}(s, d, C, \Delta t)$ is randomly selected from the nodes in the simulation topology. The BW capacity C is also randomly selected according to a uniform distribution within 12.5–200 Gb/s. The transmission reaches of BPSK, QPSK, 8-QAM, and 16-QAM signals are determined based on the experimental results reported in [7]. Table I summarizes the simulation parameters.

We first perform simulations with $g = 1$ to compare the proposed HSMR algorithms to two benchmark algorithms. Between them, one benchmark uses single-path routing, which is the exhaustive path-search RMSA (EPS-RMSA), and the other uses the split-spectrum approach [22]. The EPS-RMSA is a greedy algorithm designed by ourselves, in which we compute all feasible routing paths for the s--d pair of a request and try to serve it with an exhaustive path search. Note that we use the first-fit spectrum assignment for the proposed HSMR algorithms in the simulations.

Figs. 3 and 4 show the simulation results on BBP in the NSFNET and US Backbone topologies, respectively. We observe that the BBP curves in both figures follow the same trend. When comparing the results from the HSMR schemes with those from the benchmark algorithms, we observe that the HSMR schemes achieve significantly lower BBP for all traffic loads in both topologies.

The results also suggest that the dynamic RMSA with HSMR using online path computation (HSMR-OPC) achieves the lowest BBP among all HSMR schemes. This is attributed to the fact that HSMR-OPC optimizes routing paths for each request on the fly with considerations of the BW utilizations and lengths of links. Among the HSMR schemes that use fixed path sets, the scheme that employs the shortest path first path-selection policy (HSMR-FPS-SPF) has the highest BBP because that selecting the shortest paths to serve requests can make the network load distribution unbalanced. The HSMR-FPS schemes that employ load-balancing path-selection policies, such as the most slots first (HSMR-FPS-MSF) and the most left slots first (HSMR-FPS-MLSF), serve the requests in a more load-balanced way and outperforms HSMR-FPS-SPF. However, HSMR-FPS-MSF and HSMR-FPS-MLSF have the same drawback that they tend to use routing paths that are less congested regardless of how many hops they have. For RMSA, serving a request with a path that has more hops means that the actual usage of subcarrier slots in the network is larger, as more

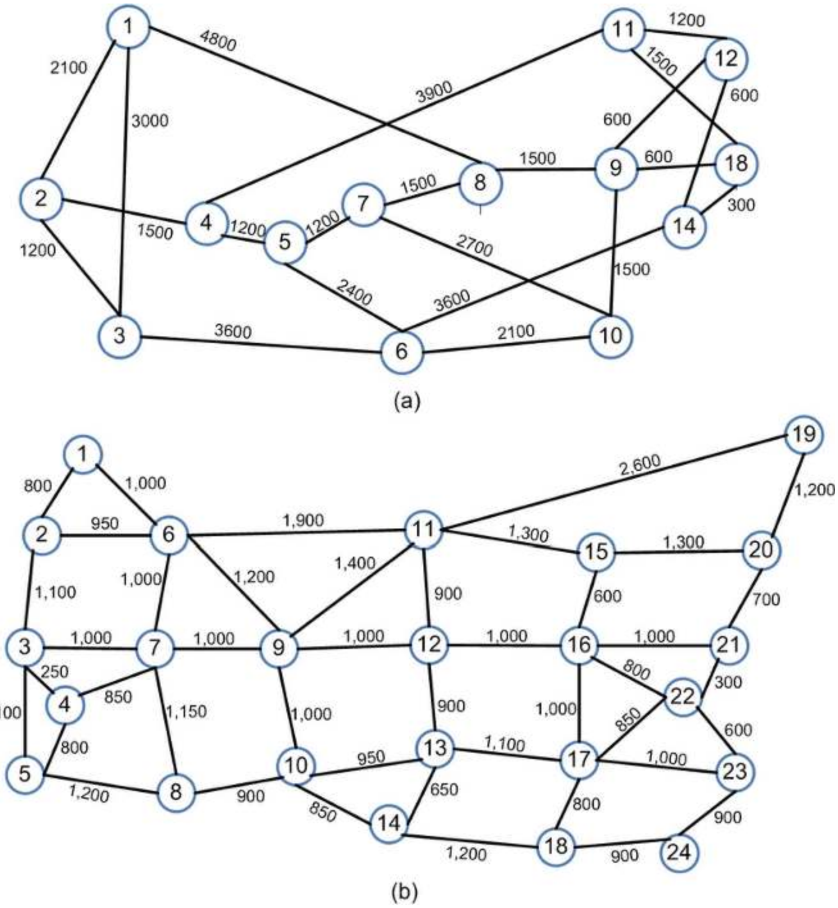

Fig. 2. Topologies used in simulations with fiber length in kilometers marked on links. (a) NSFNET topology (14 nodes). (b) US Backbone topology (24 nodes).

TABLE I
SIMULATION PARAMETERS

B, number of frequency slots per link	300
BW_{slot}, bandwidth of a frequency slot	12.5 GHz
C_{slot}, capacity of a frequency slot with $M = 1$	12.5 Gb/s
N_{GB}, number of slots for guard-band per connection	1
g, bandwidth allocation granularity	1 - 5
Transmission reach of BPSK ($M = 1$)	9,600 km
Transmission reach of QPSK ($M = 2$)	4,800 km
Transmission reach of 8-QAM ($M = 3$)	2,400 km
Transmission reach of 16-QAM ($M = 4$)	1,200 km
K, number of path candidates for a s-d pair	5
Range of requested capacity (C)	12.5 - 200 Gb/s

slots have to be allocated on additional hops. This is similar to the routing and wavelength assignment in fixed grid DWDM networks [29]. The HSMR-FPS schemes that use the largest slots-over-hops first and the largest slots-over-square-of-hops first (HSMR-FPS-LSoSHF) path-selection policies consider the balance between path length and link utilization, and hence achieve better BBP performance. The HSMR-FPS-LSoSHF obtains the best BBP performance among all HSMR-FPS schemes and its BBP performance is just slightly worse than that of HSMR-OPC.

We then investigate the BBP performance of HSMR schemes by changing g from 1 to 5. Figs. 5 and 6 show the results for the HSMR-OPC scheme in the two topologies. The BBP results of the other HSMR schemes follow the same trend. The results suggest that the BBP performance of HSMR schemes

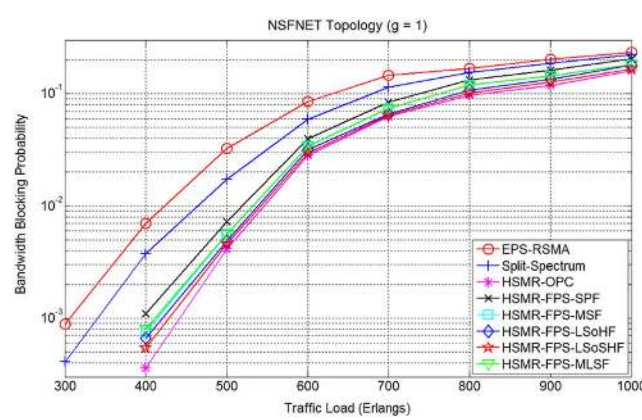

Fig. 3. Simulation results on BBP versus traffic load in NSFNET using $g = 1$ for HSMR schemes.

gets worse with a larger BW allocation granularity g. The reason behind this trend is that increasing g reduces the number of path splitting (i.e., splitting the traffic of a request over multiple paths) in the HSMR schemes. Therefore, g can be a convenient control parameter for the network operator to balance the tradeoff between request blocking and network management complexity.

The simulation results on average network throughput are plot in Fig. 7 for using HSMR-OPC $(g = 1-5)$ in the US Backbone topology. We observe that when $g \leq 3$, the HSMR-OPC

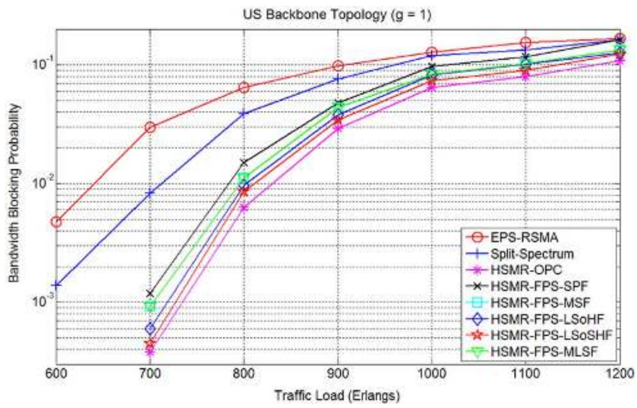

Fig. 4. Simulation results on BBP versus traffic load in US Backbone using $g = 1$ for HSMR schemes.

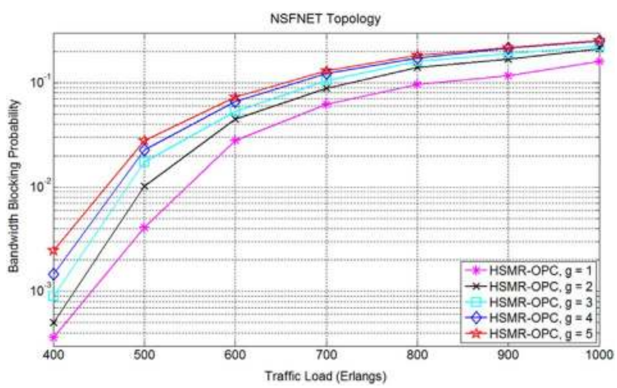

Fig. 5. Simulation results on BBP versus traffic load in NSFNET for HSMR-OPC scheme using $g = 1$–5.

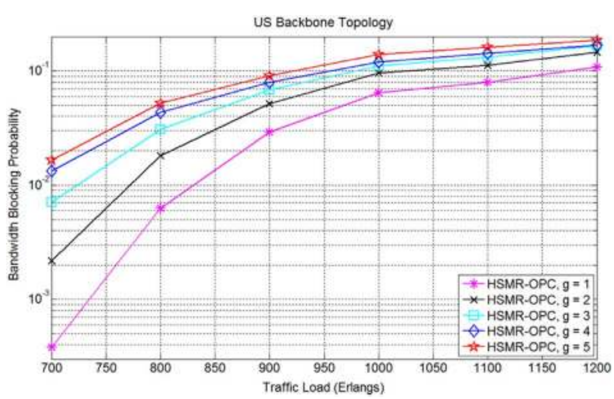

Fig. 6. Simulation results on BBP versus traffic load in US Backbone for HSMR-OPC scheme using $g = 1$–5.

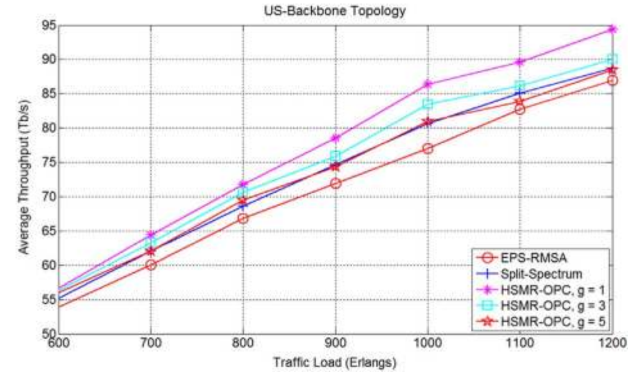

Fig. 7. Simulation results on average network throughput versus traffic load in US Backbone for HSMR-OPC scheme using $g = 1$–5.

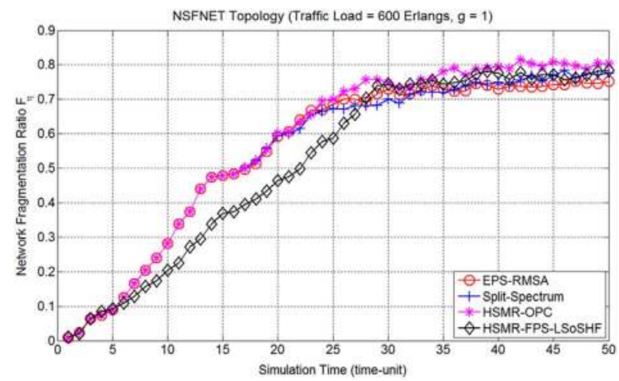

Fig. 8. Simulation results on network fragmentation ratio in NSFNET for HSMR schemes using traffic load at 600 Erlangs and $g = 1$.

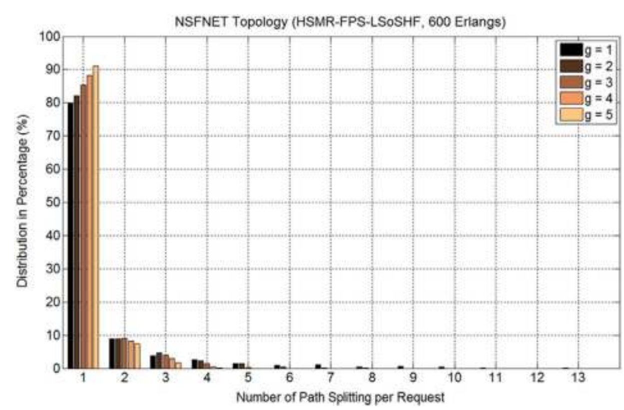

Fig. 9. Simulation results on the distribution of path splitting per request in NSFNET using the HSMR-FPS-LSoSHF scheme.

scheme achieves larger network throughput as compared to the benchmarks. The network throughput achieved by HSMR-OPC with $g = 5$ is comparable with that by the split-spectrum approach. We also study the proposed algorithms' impacts on BW fragmentation in the network. When we fix the traffic load at 600 Erlangs and set $g = 1$, Fig. 8 plots the network fragmentation ratio [defined in (6) and (7)] versus simulation time. We observe that the network fragmentation ratio from the HSMR-FPS-LSoSHF scheme increases slower than those from the two benchmark algorithms. Due to the fact that HSMR-OPC calculates routing paths on the fly, the network fragmentation ratio from it increases faster than those from the two benchmarks.

Finally, we investigate the distribution of the number of path splitting per request for the HSMR schemes. Our simulation results indicate that the distributions for different HSMR schemes are similar, and so we choose the HSMR-FPS-LSoSHF to illustrate the trend. Fig. 9 shows the distributions from the simulations using the NSFNET topology, when the traffic load is fixed at 600 Erlangs and $g = 1$–5. We can see that even for the worst case with $g = 1$, 79.80% of the requests are still served by a single routing path and the largest number of path splitting per

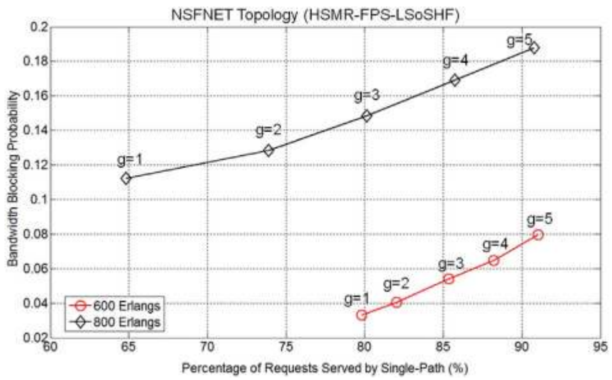

Fig. 10. BBP versus percentage of requests served by single-path in NSFNET using the HSMR-FPS-LSoSHF scheme.

request is 13. As expected, g has a clear effect on the distribution of path splitting per request. Specifically, choosing a larger g can make more requests be served by a single path and hence reduce the complexity of network management. However, as shown in Figs. 5 and 6, a larger g also results in worse BBP. Therefore, there is a tradeoff between BBP and network management complexity for our proposed HSMR schemes. Fig. 10 investigates this tradeoff for traffic loads at 600 and 800 Erlangs. The results indicate that g can be a convenient control parameter for a network operator to balance the tradeoff mentioned previously.

VI. Conclusion

In this paper, we have proposed several online service provisioning algorithms that incorporated dynamic RMSA with a HSMR scheme. Two types of HSMR schemes have been investigated: 1) HSMR-OPC, and 2) HSMR-FPS. Moreover, for HSMR-FPS, we analyzed several path selection policies to optimize the design. The proposed algorithms were evaluated with numerical simulations using a Poisson traffic model and two mesh network topologies. The simulation results verified that the proposed HSMR schemes could effectively reduce the BBP of dynamic RMSA, as compared to two benchmark algorithms that used single-path routing and split spectrum. Among all HSMR schemes, HSMR-OPC achieved the lowest BBP, while the HSMR-FPS scheme that used the HSMR-FPS-LSoSHF path-selection policy obtained the lowest BBP among all HSMR-FPS schemes. We also investigated the proposed algorithms' impacts on other network performance metrics, including network throughput and network BW fragmentation ratio. The study on the distribution of the number of path splitting per request showed that the majority of the requests were still served over a single routing path with the proposed HSMR schemes.

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