Spectrum Expansion/Contraction Problem for Multipath Routing with Time-Varying Traffic on Elastic Optical Networks

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ABSTRACT

The spectrum allocated to an end-to-end connection between source and destination nodes varies dynamically with time (denoted as *time-varying traffic*). For serving time-varying traffic in an Elastic optical network (EON), the spectrum allocated for the connection can be expanded or contracted to meet the traffic requirement. Moreover, multipath routing algorithms can more flexibly utilize spectrum resources than single-path routing algorithms in dynamic scenario, since it splits a traffic request into multiple small-size connections and individually transmitting them through several optical paths. In this paper, the *spectrum expansion /contraction problem* (SECP) for multipath routing on EONs is studied with time-varying traffic. The expansion and contraction algorithms are proposed to solve this problem and these algorithms are examined through simulations. Simulations show that the proposed algorithms can achieve good results.

CCS Concepts

•Networks → Control path algorithms; Network resources allocation;

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Keywords

spectrum expansion/contraction ; elastic optical network ; multi-path routing ; time-varying traffic

1. INTRODUCTION

Elastic optical networks (EONs), which employ *optical-orthogonal frequency division multiplexing* (O-OFDM), have been proposed to scale the demands by efficiently utilizing the spectrum as they provide finer spectrum granularity and distance adaptive modulation formatting. The spectrum of a link in EONs is divided into small unit *frequency slots* (FSs) and necessary amount of consecutive FSs for a given data rate are assigned to support the connection request. Besides, more efficient spectrum allocation is achieved in these networks due to flexible grid and elastic line rates providing finer granularity. Therefore, EON performs higher scalability and higher flexibility than *wavelength division multiplexing* (WDM) network [1, 2]. EONs provide a super-channel connectivity for accommodating ultra-high capacity demands and a sub-wavelength granularity for low-rate transmissions [1, 2]. Hence, O-OFDM can achieve subwavelength granularity, by using elastic bandwidth (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 [3]. Moreover, the modulation level of the subcarrier slots can be adaptive to accommodate various qualities of transmission [4, 5]. On EON, we need to develop *routing, modulation-level, and spectrum assignment* (RMSA) algorithms for network control and management.

Due to the *spectrum continuity constraint* [1, 2], there is a tight coupling between spectrum allocation and routing of a demand. Consequently, RMSA has emerged as the essential problem for spectrum management in EONs. A connection requiring a certain capacity should be satisfied by assigning a number of contiguous frequency slots. For a given connection request, the goal of the RMSA problem is to find a lightpath on the network and assign the frequency-slots (FSs).

1.1 Multipath Routing

Multi-path routing scheme has already demonstrated improved network performance in WDM networks [6]. For online provisioning, it is difficult to serve certain large-BW requests with single-path routing due to the BW limitation, thus resulting in high request blocking probability [7]. The elastic nature of EON enables us to split a connection's traffic over multiple routing paths without causing significant bandwidth waste. However, since the spectrum continuity and spectrum non-overlapping constraints should be considered in RMSA, multi-path provisioning in EON can be intrinsically more complicated than those in WDM network. In [8], the authors proposed a novel dynamic multi-path service provisioning algorithm that is specifically designed for EONs and considers the differential delay constraint. In Fig. 1(a), the connection request $R = (A, D, 4)$ between nodes A and D required four FSs can be achieved by two routing paths $p1$ and $p2$. The allocated FSs for these lightpaths are shown in Fig. 1(b) [6]. If multipath routing were not allowed, the request is blocked on the current network.

In [8], the authors proposed a novel dynamic multi-path service provisioning algorithm that is specifically designed for EONs and considers the differential delay constraint. In [7], authors have proposed two dynamic service provisioning algorithms that incorporate a hybrid single-/multi-path routing (HSMR) scheme (denoted as RMSA-HSMR). Which attempted to consider dynamic RMSA based on both online path computation (RMSA-OPC) and fixed path selection (RMSA-FPS) with various path selection policies for multipath provisioning in O-OFDM networks [7]. The simulation results have demonstrated that the proposed RMSA-HSMR schemes can effectively reduce the bandwidth blocking probability (BBP) of dynamic RMSA, as compared to single-path routing algorithms that use single-path routing or split spectrum.

1.2 Time-Varying Traffic

In a network, each optical connection can be transmitted by an allocated channel which consists a *central frequency* (CF) and a *channel size* (or size, FSs). The size of the channel is determined by the requested bit-rate, the modulation technique applied, the (fixed) slice width, and the guard band introduced to separate two spectrum adjacent connections, among others. In Fig. 1(c), the CF of the lightpath is set to 193.1 THz and channel size is set to 6 FSs with BW 37.5GHz (1 FS=6.25 GHz). The *spectrum allocation* (SA) on EONs differs with the DWDM channel assignment in that the channel width is not rigidly defined, but it can be tailored to the actual width of the transmitted signal.

In [9], authors defined a general spectrum allocation framework for time-varying traffic demands on EONs. Namely, they discerned three SA schemes of different levels of elasticity. These schemes put some restrictions on the accessibility of spectrum resources within the flex-grid for bandwidth-variable connections. The restrictions are applicable for both off-line (planning) and online (operation) RMSA problems concerning lightpath adaptation. These schemes are stated as follows [9]:

- *Fixed*: both the assigned CF and spectrum width do not change in time (In Fig. 1(d)). At each time period, demands may utilize either whole or only a fraction of the allocated spectrum to convey the bit-rate requested for that period.

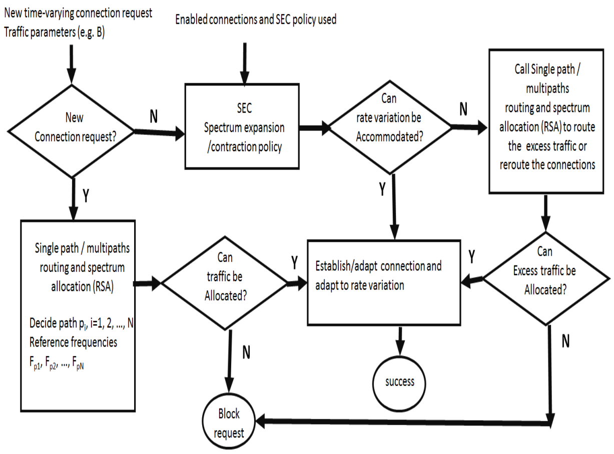

Figure 2: Flow chart of the SEC.

- *Semi-Elastic*: the assigned CF is fixed, but the allocated spectrum may vary. In this scheme, in each time interval, the allocated spectrum corresponds to the utilized spectrum. Here, spectrum increments (decrements) are achieved by allocating (releasing) frequency slices at each end of the already allocated spectrum while keeping invariant the CF. The frequency slices can be shared between neighboring demands, but used by, at most, one demand in a time interval (in Fig. 1(e)).
- *Elastic*: both the assigned CF and the spectrum width can be subject to change by performing Spectrum Expansion/Reduction in each time interval (In Fig. 1(f)).

In [9, 10], simulations showed that the elastic scheme with expansion/reduction minimizes the amount of un-served bitrate. Since the performance tradeoff of this scheme is low, spectrum Expansion/Reduction can be considered as an attractive approach for elastic SA. In this paper, the elastic scheme with expansion/reduction is used for for the multipath routing.

The rest of the paper is organized as follows. First in Section 2 the definition and assumptions of the problem are given. In Section 3, the RMSA-HSMR algorithm for multipath computation proposed in [7] is stated. In Section 4 the proposed algorithms are described (includes SEC algorithm and path selecting policy (PSP). Then, in Section 5, the performance of the proposed methods is examined. The conclusion is drawn in Section 6.

2. STUDIED PROBLEM

When the request arrived, if it is a new connection request, then the RMSA-HSMR algorithm is performed to find the set of routing paths and the assigned FSs. If the required bandwidth cannot be satisfied, then the request is blocked; Otherwise, the lightpaths are established, FSs of lightpaths are allocated. If the request is an adjusted request, based on the selected spectrum expansion/contraction policy, the selected lightpaths are adjusted. The CF and the channel size of the lightpaths are adjusted (expanded or contracted). If the rate variation can be accommodated, then the connections and rates of the lightpaths are adjusted Otherwise, the RMSA-HSMR algorithm is performed to route the excess traffic or reroute the connection. The flow chart of the

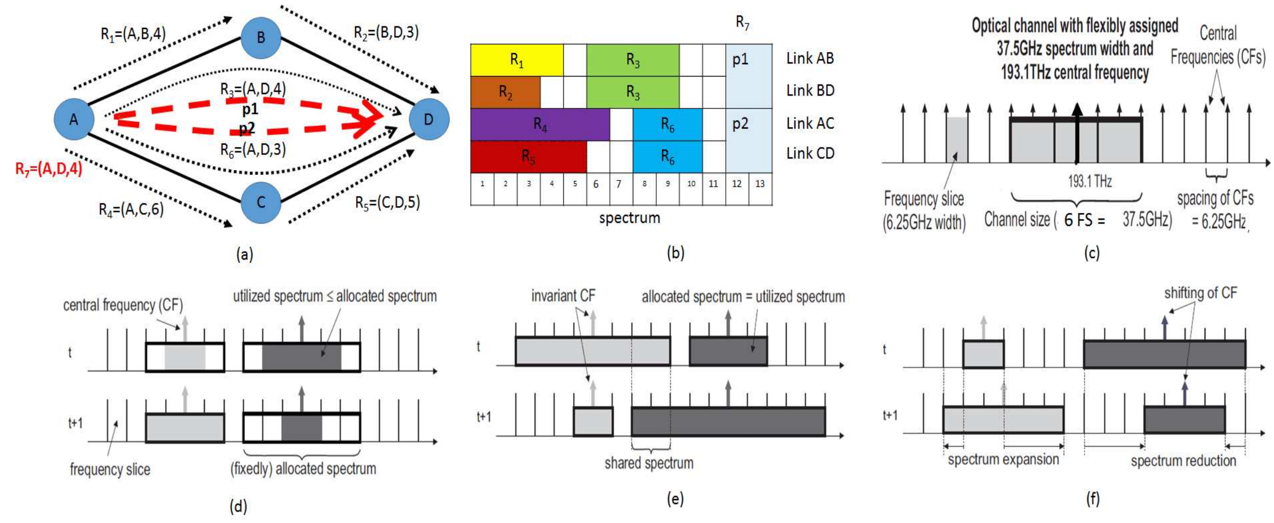

Figure 1: (a) Multipath routing, (b) spectrum allocation for multipath, (c) frequency allocation on EON, (d) fixed assignment, (e) semi-elastic, (f) elastic with expansion/contraction.

SEC algorithm for multi-path routing is shown in Fig. 2. The studied problem is for the hybrid single/multiple paths routing scheme, if the traffic of the request varies, how to adjust the lightpaths so that the network performance can be optimized.

Consider the example shown in Fig. 1(a), if the connection $R_7(A, D, -3)$ is arrived, it means that the bandwidth of the request R_7 is decreased from 4 FSs to 1 FSs. Since two lightpaths $p1$ and $p2$ are used to route the request. One of the lightpaths $p1$ and $p2$ should be deleted and the other lightpath should be contracted. In this paper, the *Spectrum Expansion/Contraction Problem* (SECP) for multipath routing with time-varying traffic on EONs is considered. For a given EON and a sequence of requests, the goal is to add/delete/expanse/contract lightpaths and assigned suitable channels to the lightpaths to meet the traffic requirement such that the performance measure can be optimized. In this paper, two algorithms are proposed to solve this problem.

In the following, the assumptions, constraints, notations and the definitions of the studied problem are given.

2.1 Assumptions

The assumptions of the studied problem are given as follows. For each link, there is a fiber connecting the end-nodes and signal can be transmitted bidirectionally. All nodes in the network are equipped with bandwidth variable wavelength cross-connects (BV-WXC). For simplicity, the numbers of FSs provided by links are all equal. The bandwidth requirement between nodes can be transmitted by using multiple lightpaths with same or different routes and numbers of frequency-slots. We assume that there is not any spectrum converter in the network.

2.2 Constraints

In this section, for a given lightpath, the same block of FSs of every link along the lightpath is allocated (called as *spectrum continuity constraint*). Sub-carriers of the same data stream must be consecutive along the frequency domain (called as *sub-carrier consecutiveness constraint*). Hence, all frequency slots assigned in a link for a given request should be adjacent in the spectrum. Allocated frequency slots for paths must be separated by guard bands in order to prevent interfering, i.e., at least one frequency slot must be assigned as a guard band between the frequency slot set of every lightpaths. Likewise, this constraint also implies that one frequency slot can be employed by only a single lightpath at a time (called as *non-overlapping spectrum assignment constraint*).

To avoid a request R from being split over too many paths, a *BW allocation granularity* (denoted as g slots) is defined [7]. Specifically, when the request R is provisioned over more than one routing paths, the minimum number of the FSs which can be allocated on each path is g. Note that increasing g eventually lead to a single-path-only scenario when g is comparable to the largest size of the requests [7].

2.3 Notations

- $G = (V, E, B, d)$: the physical topology of the network, where $V = \{v_1, v_2, ..., v_n\}$ is the set of nodes ($|V| = n$), $E = \{e_1, e_2, ..., e_m\}$ is the set of links, B is the number of frequency slots provided by each fiber, and $d(e_l)$ is length of the link $e_l \in E$. We assume that the BW of each subcarrier slot is unique as BW_{sl} GHz [7].

- M: is the modulation level in terms of bits per symbol; M can be 1, 2, 3, and 4 for BPSK, QPSK, 8-QAM, and 16-QAM, respectively.

- C_{sl}: the capacity of a slot when the modulation is BPSK (M=1) and is a function of BW_{sl} [11] and the capacity of a slot is $M \times C_{sl}$

- $R(s, d, C)$: the request, where $s \in V$ and $d \in V$ is the source and destination node of the lightpath, respectively. C is the required bandwidth (the unit of C is GHz).

- $b_l(j)$: for each link e_l in E, a B-bit bit-mask $b_l(j)$, j =1, 2, ..., B, represents the status of the j^{th} FS of the link e_l, $e_l \in E$; if the j^{th} FS is occupied, then $b_l(j) = 1$; otherwise, $b_l(j) = 0$.
- $sum(e_l)$: the summation of the bit-mask of the link e_l for all j =1, 2, ..., B, that is, $sum(e_l) = \sum_{j=1}^{B} b_l(j)$.
- M_i: For each path $p_{s,d,i} \in P$, the modulation level of the path can be derived as

$$M_i = ML\left(\sum_{e_l} d(e_l)\right), e_l \in p_{s,d,i}, \tag{1}$$

where $ML()$ 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 [4,7], and when the distance of $p_{s,d,i}$ permits, we always assign the highest modulation level to guarantee high spectral efficiency [7].

For a lightpath request $R(s, d, C)$, the RMSA-HSMR algorithm proposed in [7] with online path computation is used to determine a set of routing paths $\{p_{s,d,i}|i = 1, 2, ..., z\}$ to serve the request, where i is the index of each routing path. Note that, for different i, the routing paths can be identical, but since their spectrum allocations are not contiguous, more than one sets of O-OFDM transceivers are required.

3. MULTIPATH COMPUTATION

In this section, the details of the RMSA-HSMR algorithm proposed in [7] with online path computation are described. For a new connection request $R(s, d, C)$, the set $\{p_{s,d,i}|i = 1, 2, ..., z\}$ of lightpaths should be established to route the request. First, the status of the links of the current network are updated. The network $G(V, E, B, d)$ is then transformed to a graph $G'(V, E, d')$, where the weight $d'(e_l)$ of link e_l is calculated according to the link spectrum usage and by using the formula

$$d'(e_l) = \begin{cases} +\infty, & MaxBlock(e_l) \le g \\ w_l \times \frac{sum(b_l)+g}{B}, & MaxBlock(e_l) > g, \end{cases} \tag{2}$$

where g is the BW allocation granularity, $MaxBlock(e_l)$ is the maximal number of continuous free frequency-slots on link e_l, $sum(b_l)$ returns the current spectrum usage of link e_l, and w_l is calculated from $d(e_l)$ with

$$w_l = ML_{max} - ML\left(d(e_l)\right) + 1, \tag{3}$$

where ML_{max} is the highest modulation level that can be supported in the network, and $ML()$ is defined in (1) to return the highest modulation level that a transmission distance can support [7]. Since a higher modulation means a less number of slots to allocate and better utilization of network spectrum resource, the value $d(e_l)$ is converted to $ML(d(e_l))$ and mapped to w_l to calculate the routing path. A link e_l is omitted from the online path computation, if it does not have a block of available contiguous slots with the size $> g$. Otherwise, the link weight $d'(e_l)$ is proportional to the product of w_l and the number of used slots $sum(b_l)$.

For the connection request $R(s, d, C)$, the K-shortest paths algorithm [12] is performed on the network $G'(V, E, d')$ to find a set of candidate paths $P = \{(p_{s,d,i}), i = 1, 2, ..., K\}$. Paths in P are sorted in ascending order according to the distances of the paths $\sum_{e_l \in p_{s,d,i}} d(e_l)$ on network $G(V, E, B, d)$. After the candidate path is selected, the last step of RMSA-HSMR is the spectrum assignment to finalize the allocations of contiguous slots along the fiber links on $p_{s,d,i}$. The spectrum assignment on $p_{s,d,i}$ is to find N_i contiguous bits based on current value b_l of link e_l in $p_{s,d,i}$. The set of routing paths for request $R(s, d, C)$ is denoted as $P^{new} = \{(p_{s,d,i}, M_i, N_i), i = 1, 2, ..., z\}$. The load C_i allocated to the selected path $p_{s,d,i} \in P^{new}$ is determined based on the network status and should satisfy the constraint $C = \sum_{\forall p_{s,d,i} \in P^{new}} C_i$. The number of assigned contiguous FSs N_i for the path $p_{s,d,i}$ is computed by $N_i = \lceil C_i/(M_i \times C_{sl}) \rceil + N_{GB}$, where N_{GB} is the number of FSs for the guard band. Note that when the traffic is routed by multiple paths, more FSs will be used for the guard band. In the context of this study, we assume that $N_{GB} = 1$ and this guard band is inserted as the highest indexed slot in the spectrum assignment of each connection. The request R is blocked, if a feasible set of routing paths $\{(p_{s,d,i}, M_i, N_i), i = 1, 2, ..., z\}$ cannot be found. The detailed of the RMSA-HSMR algorithm are shown in Algorithm 1.

Algorithm 1 RMSA-HSMR Algorithm [7]

Input: $G(V, E, B, d)$, $R(s, d, C)$;
Output: the set of lightpaths $P^{new} = \{(p_{s,d,i}, M_i, N_i), i = 1, 2, ..., z\}$
$P^{new} = \emptyset$;
collect link status of network $G(V, E, B, d)$;
restore network resources used by expired requests;
update link weights $d'(e_l), \forall e_l \in E$ based on the current network status, using formulae (2) and (3);
construct graph $G'(V, E, d')$;
read the incoming request $R(s, d, C)$;
calculate a set $P = \{p_{s,d,i}, i = 1, 2, ..., K\}$ of K-shortest routing paths from s to d on $G'(V, E, d')$;
sort the paths in P in ascending order based on the distances $\sum_{e_l \in p_{s,d,i}} d(e_l)$, $\forall p_{s,d,i} \in P$;
for all ($p_{s,d,i}$ in P) **do**
  {
  determine the highest modulation level M_i for the path $p_{s,d,i}$ with its real distance $\sum_{e_l \in p_{s,d,i}} d(e_l)$ using (1);
  for all (all available slot blocks with sizes $> g$) **do**
    {
    allocate maximal allocatable capacity C_i to slot blocks with N_i;
    add path $(p_{s,d,i}, M_i, N_i)$ to P^{new};
    if ($\sum_{p_{s,d,i} \in P^{new}} = C$) **then**
      break inner and outer for-loops;
    end if
    }
  end for
  }
end for
if ($\sum_{p_{s,d,i} \in P^{new}} C_i < C$) **then**
  revert all the spectrum allocations;
  remove all paths from P^{new}, mark the request as block;
  return false;
end if
return success and $P^{new} = \{(p_{s,d,i}, M_i, N_i)\}$;

4. SEC ALGORITHM

In this section, the *Path Selecting Policy (PSP)* and two algorithms (named as *Expanse Algorithm* and *Contract Algorithm*) are proposed to do the SEC operation. The proposed algorithms are described in the following subsections.

4.1 Path Selecting Policy (PSP)

When an adjusted connection request, since the request may be currently routed by multipath, several lightpaths can be selected to expanse or contract to meet the requirement. Though, the path-selection policies should be designed to select the current lightpaths for expansion or contraction. The priority or sequence of the selected paths can be determined by the PSPs.

The PSP for Expansion Algorithm are listed as follows:

- *Minimal Fragmentation Ratio First (MinFRF)*: The routing path with minimal *fragmentation ratio* will be selected first. The link fragmentation ratio is usually introduced to describe the spectrum occupation of link [13]. The *fragmentation ratio* of a path $p_{s,d,i}$ is the ratio of the summation of the maximal number of continuous free frequency-slots $MaxBlock(e_l)$ on link $e_l \in p_{s,d,i}$ to the summation of the number of free frequency-slots on link $e_l \in p_{s,d,i}$. It can be computed by the following formula:

$$FR_{p_{s,d,i}} = \frac{\sum_{\forall e_l \in p_{s,d,i}} MaxBlock(e_l)}{\sum_{\forall e_l \in p_{s,d,i}} (B - sum(e_l))}. \qquad (4)$$

- *Maximal Available Slots First (MaxASF)*: The path with maximal total available slots is selected first. The number of available slots on a path can be computed by

$$AS(p_{s,d,i}) = \sum_{\forall e_l \in p_{s,d,i}} (B - sum(b_l)). \qquad (5)$$

- *Shortest Path First (SPF)*: We select the paths in the ascending order based on the length of the path:

$$LoP = \sum_{\forall e_l \in p_{s,d,i}} d'(e_l). \qquad (6)$$

The PSPs for Contraction Algorithm are listed as follows:

- *Maximal fragmentation Ratio First (MaxFRF)*: The routing path with maximal *fragmentation ratio* will be selected first.
- *Largest Weighted Distance Path First (LWDPF)*: We select the paths in the ascending order based on the weighted length of the path:

$$WD = \sum_{\forall e_l \in p_{s,d,i}} d(e_l) \times \sum_{\forall e_l \in p_{s,d,i}} sum(e_l). \qquad (7)$$

4.2 Expansion Algorithm

When the bandwidth of the request increases, the bandwidth of current supporting lightpaths should be increased or a (or several) new lightpath(s) with suitable modulation level should be established with suitable FSs. In this paper, the allocated FSs of current lightpaths are expanded first, if possible. After performing expansion, if the bandwidth cannot be fully supported, a set of new lightpaths is added to route the un-supported bandwidth.

We assume that the new request is represented by (s, d, C^{new}), the set of current lightpaths used to support the request is represented be $P = \{(p_{s,d,i}, C_i, M_i) | i = 1, 2, ..., z\}$, where C_i is the bandwidth provided by the lightpath, M_i is the modulation level of the lightpath and $C' = \sum_{\forall p_{s,d,i} \in P} C_i$. If $C^{new} > C'$ (or $C^e = C^{new} - C' > 0$), then the lightpath expansion process will be repeated. Based on the path selecting policy, a lightpath p in P is selected to expand. The elastic scheme is used to expand the required FSs, that is, the CF or the size of the channel can be adjusted. If there is not any path $p \in P$ can be expanded, then the remaining required bandwidth will be supported by new lightpaths found by performing the RMSA-HSMR algorithm.

Algorithm 2 Expansion Algorithm

Input: $G(V, E, B, d)$, $P = \{(p_{s,d,i}, C_i, M_i) | i = 1, 2, ..., z\}$, (s, d, C^{new}), path selecting policy (PSP);
Output: P^{new};
Restore network resources used by expired requests.
Calculate the total bandwidth provided by the set of current lightpaths $C' = \sum_{\forall p_{s,d,i} \in P} C_i$ and difference $C^e = C^{new} - C'$.
while $(C^e > 0)$ **do**
  {
  Select a path p in P with highest priority according to the PSP.
  if (path p cannot be found) **then**
    {
    //add new lightpaths
    Perform **RMSA-HSMR algorithm** to find a set P' of new lightpaths with bandwidth C^e between nodes s and d.
    if (the set P' can be found) **then**
      Add lightpaths in P' to P^{new}.
      $P^{new} = P^{new} \cup P$ and **return success**.
    else
      Block the request and **return false**.
    end if
    }
  else
    {
    //expand FSs of lightpath
    Find the maximal expandable FSs FS_{max} for the selecting lightpath p and the requires FS_e
    Determine the number of FSs to be expanded and the bandwidth C_p can be provided, i.e., $F_p = \max\{F_{max}, FS_e\}$.
    Update $C^e = C^e - (F_p - N_{GB}) \times ML(p) \times C_{sl}$.
    Expand the channel size and adjust CF of the lightpath p, remove p from P and add p to P^{new}.
    }
  end if
  }
end while
$P^{new} = P_{new} \cup P$ and **return success**.

4.3 Contraction Algorithm

When the bandwidth of the request decreases, the bandwidth of current supporting lightpaths should be decreased or a (or several) lightpath(s) w should be deleted. In this paper, the allocated FSs of current lightpaths are decreased first, if possible.

We assume that the new request is represented by (s, d, C^{new}), the set of current lightpaths used to support the request is represented by $P = \{(p_{s,d,i}, C_i, M_i) \; | i = 1, 2, ..., z\}$, where C_i is the bandwidth provided by the lightpath, M_i is the modulation level of the lightpath and $C' = \sum_{\forall p_{s,d,i} \in P} C_i$. If $C^{new} < C'$ (or $C^c = C' - C^{new} > 0$), then the lightpath contraction process will be repeated. Based on the path selecting policy, a lightpath p in P is selected to contract. It is worth noting that, after contraction, the number of allocated FSs of the lightpath should be greater than or equal to g. The elastic scheme is used to contract the required FSs, that is, the CF or the size of the channel can be adjusted.

5. SIMULATION RESULTS

The NSFNET network was used for simulations. The topology of the network is shown in Fig. 3, the number nears

Algorithm 3 Contraction Algorithm

Input: $G(V,E,B,d)$, $P = \{p_{s,d,i}, C_i, M_i | i = 1,2,...,z\}$, (s,d,C^{new}), path selecting policy (PSP);
Output: P^{new};
Restore network resources used by expired requests.
Calculate the total bandwidth provided by the set of current lightpaths $C' = \sum_{\forall p_{s,d,i} \in P} C_i$ and difference $C^c = C' - C^{new}$.
if $(C^{new} == 0)$ **then**
  Remove all lightpaths in P, restore network resources of lightpaths and **return**.
end if
while $(C^c > 0)$ **do**
  Select a path p in P with highest priority according to the PSP.
  Find the bandwidth C_p provided by the selecting lightpath p.
  if $(C_p \le C^c)$ **then**
    Remove lightpath p from P.
    Update $C^c = C^c - C_p$.
  else if $(C_p - C^c \ge g)$ **then**
    Determine the number of FSs to be contracted for lightpath p.
    $C^c = 0$.
    Update lightpath p, remove p from P and add p to P^{new}
  else if $(0 < C_p - C^c < g)$ and $(g > 1)$ **then**
    Reduce the bandwidth of the lightpath p to g.
    Update $C^c = C^c - (C_p - g \times ML(p) \times C_{sl})$.
  end if
end while
$P^{new} = P_{new} \cup P$ and return success.

the line represents the distance of the link and the unit of the distance is kilometers (km). The proposed algorithms were coded by using C++ programming language and the boost graph library (BGL) [14] with version. All simulations were run on a personal computer with Intel Xeon E3-1230v3 3.30 GHz CPU, 16.0 GB RAM and with Windows 10 pro 64-bit operating system.

The BW capacity 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 the same as the [7]. Table 1 summarizes the simulation parameters. For the simulations, 1000/3000 requests are randomly generated. Each pair of nodes $(s,d) \in V \times V$ has the equal probability to be selected as the source-destination pair. The first 100 connections are new or BW increasing connections, after that, about 1/2 connections are with zero BW (the allocated lightpaths will be deleted) or are expanded/contracted connections.

Table 1: Simulation Parameters.

Name or Notation of Parameter	Setting Value
number of requests	1000 or 3000
B, number of frequency slot per link	600 or 300
BW_{sl}, bandwidth of a frequency slot	6.25 or 12.5GHz
C_{sl}, capacity of a frequency slot with M=1	6.25 or 12.5GHz
N_{GB}, number of slots for GB per conn.	1
g, bandwidth allocation granularity	1, 2, 5, 8
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

5.1 Performance Criteria

Several performance criteria are considered in this paper, they are:

- Blocking Probability (BP): BP is defined as the ratio of blocked connection BW versus total request BW.

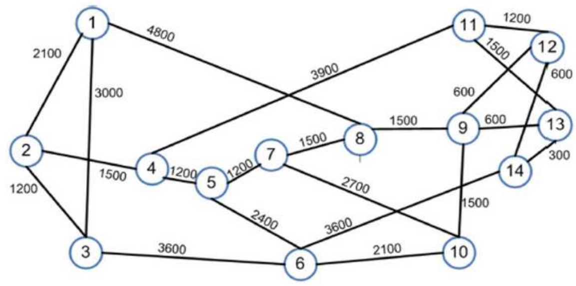

Figure 3: NSFNET.

BBP is a commonly used metric for assessing the performance of service provisioning algorithms.

- Fragmentation Ratio (FR): fragmentation is another interesting factor to investigate in dynamic RMSA.

  The fragmentation ratio of the network is defined as

$$FR = \frac{\sum_{\forall e_l \in E} MaxBlock(e_l)}{\sum_{\forall e_l \in E}(B - sum(e_l))}. \quad (8)$$

- Computation time.

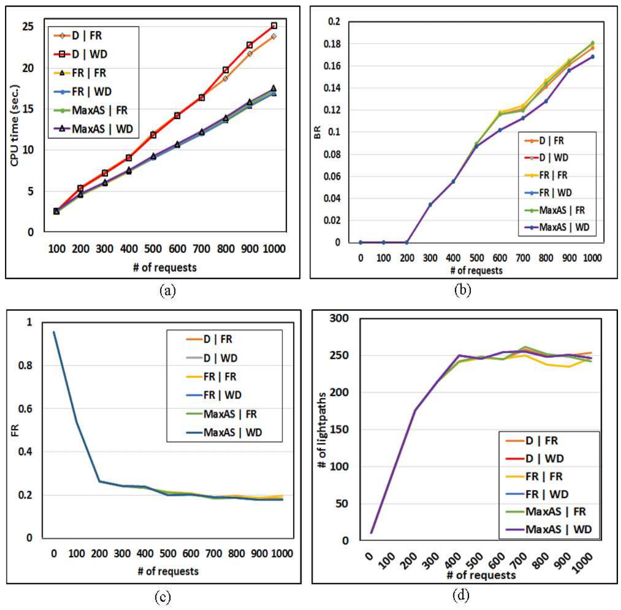

Figure 4: Simulation results for 1000 requests with different E|C PSPs: (a) CPU time in seconds, (b) BR, (c) FR, (d) number of active lightpaths.

5.2 Simulations

Six cases of the combined priorities for Expansion / Contraction are used and each of which is represented by the form "expansion|contraction". We use "D" for Shortest Path First (SPF), "FR" for Minimal/Maximal fragmentation ratio first, "WD" for Largest Weighted Distance Path First, "MaxAS" for Maximal Available Slots First. Thus, the six

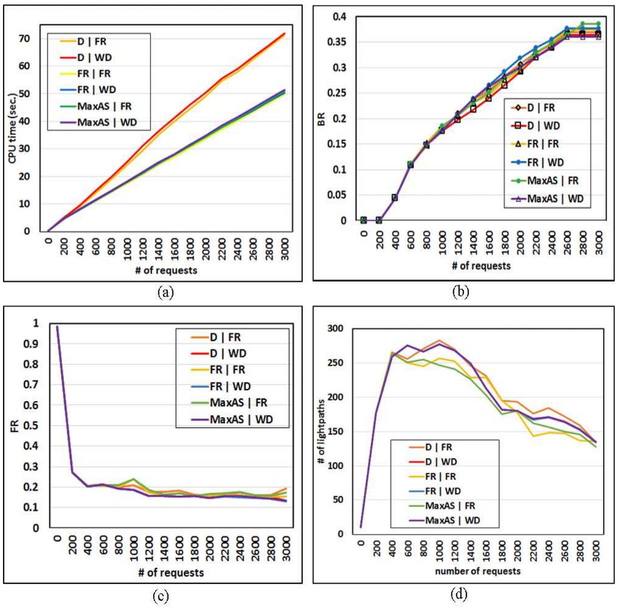

Figure 5: Simulation results for 3000 requests with different different E|C PSPs: (a) CPU time in seconds, (b) BR, (c) FR, (d) number of active lightpaths.

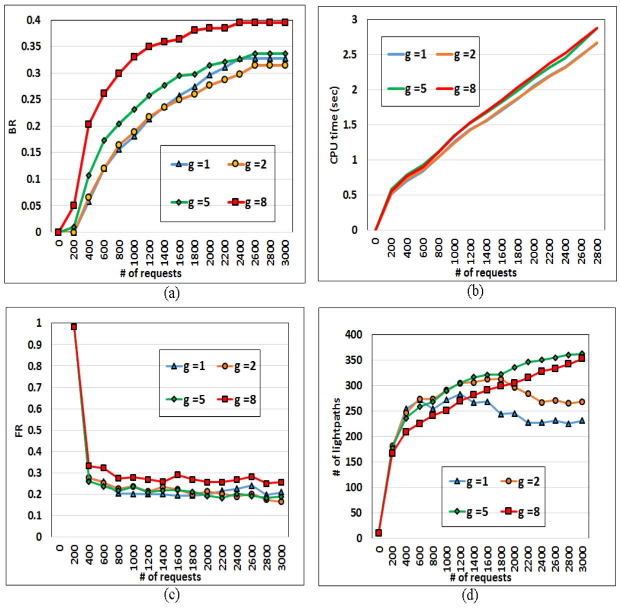

Figure 6: Simulation results for 3000 requests with different values of g: (a) BR, (b) CPU time in seconds, (c) FR, (d) number of active lightpaths.

cases are D|FR, D|WD, FR|FR, FR|WD, MaxAS|FR and MaxAS|WD.

First, 1000 connection requests are used for simulation and the results are shown in Figure 4. Figure 4(a) shows that the D|WD and D|FR are more slower than other cases. Figure 4(b) shows that the FR|WD can get lowest BR than other cases. Figure 4(c) shows that the fragmentation ratio of these cases is almost the same. Figure 4(d) shows that the FR|FR established less number of lightpaths than other cases. Then, 3000 connection requests are used for simulation and the results are shown in Figure 5. In this simulation, it can get the similar result as the results obtained by running 1000 requests.

The simulation results of 3000 connection requests and different values of $g \in \{1, 2, 5, 8\}$ are shown in Fig. 6. In Fig. 6(a), for most of the cases, as the value of g increases, the BR increases. Since the value of g represents the minimal number of FSs of a lightpath, greater g will cause the lightpath with smaller FSs cannot be blocked. Moreover, the BR of the case with $g = 2$ is the best one, even better than the case with $g = 1$. This may be the reason that lightpaths with smaller BW (g=1) are allowed to be established may cause the number of guard bands increases and bandwidth waste. Fig. 6(a) shows the computation time of simulations with different values of g, the CPU time of these cases is almost the same. Fig. 6(c) shows the FR of the network for simulations with different values of g. The case with g=8 can get larger FR than the other cases. Fig. 6(d) shows the number of active lightpaths on the network for simulations with different values of g. The cases with $g = 5$ or 8 are better than the cases with $g = 1$ or 2.

To know the effectiveness of the C_{sl} and g, two cases with $C_{sl} = 6.25$ and 12.5 GHz are combined with two cases with g=1 or 2. For the case with $C_{sl} = 6.25$ and 12.5, the value of B is set to 600 and 300, respectively. That is, for a connection $R(s, d, C)$, the required FSs will be different. The required number of FSs for the case with $C_{sl} = 6.25$ may be close the twice of the case with $C_{sl} = 12.5$. The simulation results are shown in Fig. 7. In Fig. 7(a), for the case with same C_{sl} but different g, the BR of the cases with $g = 2$ is lower than that of the cases with $g = 1$. In the case with same g but different C_{sl}, the BR of the cases with $C_{sl} = 12.5$ is lower than that of the cases with $C_{sl} = 6.25$.

In Fig. 7(b), for the case with same C_{sl} but different g, the FR of the cases with $g = 1$ is higher than that of the cases with $g = 2$. For the case with same g but different C_{sl}, the BR of the cases with $C_{sl} = 6.25$ is lower than that of the cases with $C_{sl} = 12.5$.

In Fig. 7(c), for the case with same C_{sl} but different g, the computation time of the cases with $g = 1$ is smaller than that of the cases with $g = 2$. In the case with same g but different C_{sl}, the computation time of the cases with $C_{sl} = 6.25$ is lower than that of the cases with $C_{sl} = 12.5$.

In Fig. 7(d), for the case with same C_{sl} but different g, the number of active lightpaths of the cases with $g = 1$ is smaller than that of the cases with $g = 2$. In the case with same g but different C_{sl}, the number of active lightpaths of the cases with $C_{sl} = 6.25$ is lower than that of the cases with $C_{sl} = 12.5$.

6. CONCLUSIONS

In this paper, the spectrum expansion/contraction problem for multipath routing with time-varying traffic on EONs has been studied. For a given EON and a set of connection requests, the goal is to design a spectrum expansion and contraction method to update the CF and the channel size of the lightpath so as to fit the required of the request. In the studied problem, the multiple-path routing scheme is used. The expansion and contraction algorithms are pro-

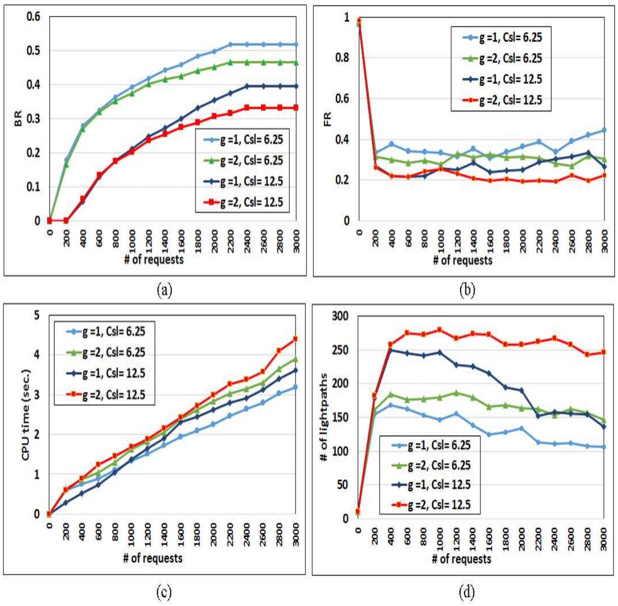

Figure 7: Simulation results for 3000 requests with different values of g and C_{sl}: (a) BR, (b) FR, (c) CPU time in seconds, (d) number of active lightpaths.

posed and several path selecting policies are designed. Simulations were conducted to evaluate the performance of the proposed algorithms.

7. ACKNOWLEDGMENTS

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