Bandwidth Defragmentation in Dynamic Elastic Optical Networks with Minimum Traffic Disruptions

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***Abstract*—Bandwidth defragmentation, *i.e.*, the operation to reconfigure existing connections for making the spectrum usage less fragmented and less misaligned, has recently been recognized as one of the most important features for elastic optical networks (EONs). In this paper, we propose a novel comprehensive bandwidth defragmentation algorithm that considers the problems of 1) *When to defragment?* 2) *What for defragment?* and 3) *How to defragment?* jointly. The proposed algorithm accomplishes defragmentation through proactive network reconfiguration that only reroutes a portion of existing connections. In each defragmentation operation, we first choose the connections to reroute using a selection strategy, then determine how to reroute them with the defragmentation based routing and spectrum assignment (DF-RSA), and finally perform rerouting with best-effort traffic migration to minimize traffic disruptions. Simulation results indicate that in order to make the bandwidth blocking probability (BBP) comparable with that from the Greenfield scenario (100% rerouting all the time), the proposed algorithm only needs to reroute ∼30% existing connections. The simulations also demonstrate that the traffic disruption percentages are less than 1% for defragmentations with 30% rerouting and can be further reduced to within 0.25% by adding a move-to-vacancy (MTV) approach in the traffic migration.**

***Index Terms*—Elastic optical networks (EONs), Bandwidth defragmentation, Traffic migration, Traffic disruption**

I. Introduction

Recently, elastic optical networks (EONs) based on the optical orthogonal frequency-division multiplexing (O-OFDM) technology [1] have attracted intensive research interests due to the high bandwidth efficiency and sub-wavelength granularity. Even though O-OFDM is considered as a potential substitute for wavelength-division multiplexing (WDM), its elastic nature also requires new network control and management procedures for efficient and robust network operation [2]. One typical example is the bandwidth defragmentation in dynamic EONs [3]. Since EONs allocate spectrum based on contiguous subcarrier slots (*i.e.*, slot-blocks) with bandwidths at a few GHz or even narrower [4], dynamically setting up and tearing down connections can generate bandwidth fragmentation. Bandwidth 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 EONs. As they are neither contiguous in the spectrum domain nor aligned along the routing paths, these slot-blocks can hardly be utilized for future connection requests and make dynamic EONs deviate from their optimal operation points. Hence, bandwidth defragmentation is critical for reducing the blocking probability of future requests.

Fig. 1 shows an intuitive example of bandwidth defragmentation. Suppose we need to set up a connection over a routing path that traverses through three fiber links, *i.e.*, L_1, L_2, and L_3. Each fiber link can accommodate 12 subcarrier slots at most. For the spectrum usage illustrated in Fig. 1(a), there are available slots on every single link but the connection will still be blocked due to the reason that none of the available slots is aligned along the path. Now, if we invoke bandwidth defragmentation and reorganize the spectrum usage to that in Fig. 1(b), slots 5-12 are freed out for future connections over (L_1, L_2, L_3). Similar to the traffic reconfiguration in dynamical WDM networks [5], a comprehensive bandwidth defragmentation algorithm needs to address three questions properly: 1) *When to defragment?* 2) *What for defragment?* and 3) *How to defragment?*

Bandwidth defragmentation in dynamic EONs only starts to attract research interests since recently. Several previous works focused on the link-based bandwidth defragmentation schemes that employ all-optical spectrum converters for partial rerouting [3, 6, 7]. Even though they are more flexible than those using path-based end-to-end rerouting, these schemes impose additional equipment costs from the spectrum converters. Moreover, the experimental results in [6, 7] indicated that the all-optical spectrum converters could introduce relatively large power penalty ($>$ 6 dB), which would make them immature for practical applications.

On the other hand, the majority of previous works on bandwidth defragmentation were based on path-based end-to-end rerouting [8–10]. Specifically, defragmentation tears down an existing connection from its source node and reroutes it in an end-to-end manner. In [8], Patel *et al.* formulated the problem of bandwidth defragmentation in flexible optical WDM networks with an integer linear programming (ILP) model and proposed two heuristics. The proposed algorithms reconfigure all connections in a sequential way such that they are optimized and rerouted one by one. This scheme, however, may result in a sub-optimal solution as the connections are not optimized jointly. A bandwidth defragmentation algorithm that considered traffic migration in dynamic EONs was discussed in [9]. This approach invokes traffic reconfiguration when a request is blocked, only targeting for provisioning the request successfully. Hence, the EON can be reconfigured

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too frequently, as each reconfiguration is optimized for a given request but not the overall network. In [10], Zhang *et al.* proposed a bandwidth defragmentation scheme based on the spectrum compactness (SC), *i.e.*, bandwidth fragmentation ratio. When an EON's SC is larger than a preset threshold, defragmentation is invoked to reduce the SC network-wide. However, it is still not clear whether a larger SC can lead to a higher request blocking probability in EONs, as suggested in [11]. Hence, the question of *When to defragment?* was not addressed properly.

In this paper, we propose a novel comprehensive bandwidth defragmentation algorithm that considers the problems of *When*, *What* and *How* jointly. As dynamically setting up and tearing down connections is the major factor to cause bandwidth fragmentation in EONs, we choose the timing of defragmentation based on the traffic load. Specifically, a defragmentation operation is invoked when the number of expired requests exceeds a preset threshold. The actual defragmentation operation employs proactive network reconfiguration that reroutes only a portion of the existing connections. To solve the routing and spectrum assignment (RSA) problem for connection rerouting, we develop a defragmentation based RSA (DF-RSA) approach that is based on K-shortest path routing and spectrum pre-allocation. In conjunction with an effective connection selection strategy, this approach can consolidate spectrum utilization effectively, as shown in our simulation results latter. After obtaining the new RSA for each selected connection, we construct a connection dependency graph and perform rerouting with best-effort traffic migration according to it to minimize traffic disruptions. We evaluate the proposed algorithm using dynamic network simulations based on the NSFNET topology and Poisson traffic model. Simulation results indicate that the algorithm can reduce the bandwidth blocking probability effectively while minimizing traffic disruptions.

The rest of the paper is organized as follows. Section II formulates the problem of bandwidth defragmentation in dynamic EONs and presents the overall procedures of the proposed algorithm. In Section III, we develop two strategies for selecting existing connections to reroute during the defragmentation. The defragmentation based RSA and the best-effort traffic migration are addressed in Sections IV and V. Section VI shows the simulation results for performance evaluations. Finally, Section VII summarizes the paper.

II. Bandwidth Defragmentation Procedures

Consider a EON network topology as $G(V, E)$, where V is the node set and E is the fiber link set. We assume that each fiber link can accommodate B subcarrier slots, and hence for each link $e \in E$, we define a bit-mask b_e with B bits to illustrate its spectrum usage [12]. When the j-th slot on e is taken, $b_e[j] = 1$, otherwise, $b_e[j] = 0$. A dynamic connection can be modeled as $C(R_{s,d}, a, t_{in}, t_{out})$, where $R_{s,d}$ is the routing path from node s destined to d, a is a B-bit bit-mask to represent the spectrum assignment, t_{in} and t_{out} are the time instants for setting up and tearing down, respectively. When

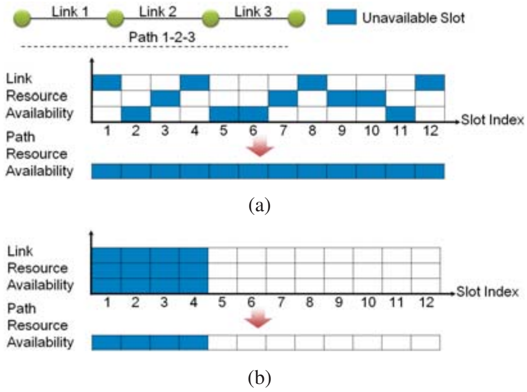

Fig. 1. An example of bandwidth defragmentation in an EON.

$a[j] = 1$, the j-th slot is allocated for C, otherwise, $a[j] = 0$. Notice that we assume there is no spectrum converter in the EON and the connections have to be provisioned all-optically end-to-end.

Algorithm 1 shows the overall procedures of the proposed bandwidth defragmentation algorithm. When the EON is in normal operation between two defragmentations, the algorithm tracks the number of expired connections (as shown in *Lines* 3-6). Here, C_i refers to the i-th connection request, where i is its unique index. A defragmentation is triggered when the number exceeds a preset threshold TH. *Lines* 8-9 explain the procedures for selecting connections to reroute, where γ is the preset selection percentage, $\mathbb{C}$ is the set of existing connections, $\mathbb{C}_s$ is the set of selected connections, and $|\cdot|$ returns the number of elements in a set. Basically, if it is selected according to a selection strategy, C_i becomes $C_{s,i}$ and is stored in $\mathbb{C}_s$. Two selection strategies are discussed in Section III.

To reroute all $C_{s,i} \in \mathbb{C}_s$ for defragmentation, we re-optimize them with a defragmentation based RSA (DF-RSA), which is discussed in Section IV. Notice that in order to minimize traffic disruptions, we would not commit the DF-RSA's output immediately. The new RSA of $C_{s,i}$, *i.e.*, $\{R'_{s,d,i}, a'_i\}$, is temporarily stored as shown in *Line* 11. *Lines* 12-14 explain the procedures of how to perform best-effort traffic migration based on a dependency graph for minimizing traffic disruptions. The details of the best-effort traffic migration are discussed in Section V. Different from the sequential rerouting scheme that only considers one existing connection at a time [8], our scheme optimizes multiple ones simultaneously. Finally, we add up traffic disruptions and reset the counter of expired connections.

III. Connection Selection Strategies

Similar to the Greenfield reconfiguration approach for WDM networks [13], reconfiguring all existing connections in an EON can reduce future blocking probability to the maximum extent. However, the Greenfield approach is usually associated with overwhelming network operations and excessive traffic disruptions. To avoid these disadvantages, we choose a semi-

Algorithm 1 Comprehensive Bandwidth Defragmentation

$k = 0$;
while the EON is operational **do**
  if an C_i expires **then**
    release resources assigned to the C_i;
    $k = k + 1$;
  end if
  if $k > TH$ **then**
    select $\gamma \cdot |\mathbb{C}|$ connections for rerouting based on a selection strategy;
    store the selected connections in $\mathbb{C}_s$;
    re-optimize RSA of all $C_{s,i} \in \mathbb{C}_s$ with DF-RSA;
    store DF-RSA's output for each $C_{s,i}$ as $\{R'_{s,d,i}, a'_i\}$;
    construct a dependency graph based on $\{R_{s,d,i}, a_i\}$ and $\{R'_{s,d,i}, a'_i\}$ of each $C_{s,i}$;
    perform best-effort traffic migration based on the dependency graph;
    reroute each $C_{s,i}$ according to $\{R'_{s,d,i}, a'_i\}$;
    count traffic disruptions;
    $k = 0$;
  end if
end while

Greenfield approach and try only to reroute a certain portion (denoted as γ) of the existing connections. As all defragmentation operations are based on the selected connections $\mathbb{C}_s$, the connection selection strategy becomes vital for our algorithm. A well-designed selection strategy should choose the most "critical" connections for rerouting. In the following Subsections, we investigate two strategies for this goal.

A. Most Frequently Used Slot First (MFUSF) Strategy

The frequency of a slot being used in the EON can be defined as in Eqn. (1). *Algorithm 2* shows the procedures of the most frequently used slot first (MFUSF) connection selection.

$$f_j = \frac{\sum\limits_{e \in E} b_e[j]}{|E|}, \quad j = 1, ..., B \tag{1}$$

B. Highest Used Slot-Index First (HUSIF) Strategy

The highest used slot-index first (HUSIF) connection selection strategy directly sorts the existing connections $C_i \in \mathbb{C}$ based on $hidx(a_i)$ in descending order, and chooses the first $\gamma \cdot |\mathbb{C}|$ connections as $\mathbb{C}_s$. Here, $hidx(\cdot)$ returns the highest index of bit "1" in a bit-mask.

IV. Defragmentation based RSA

After selecting the connections to reroute, we apply a DF-RSA to re-optimize their RSA. The DF-RSA tries to move the connections to slots with lower indices and to open up more upper-portion spectrum for accommodating future connections. The DF-RSA incorporates a spectrum pre-allocation scheme similar to that in [14] to consolidate spectrum usage to one side greedily. *Algorithm 3* illustrates the detailed procedures of the DF-RSA.

Algorithm 2 Most Frequently Used Slot First Connection Selection

calculate usage frequency f_j for all slots $j = 1, ..., B$;
$k = 0$, $\mathbb{C}_s = \emptyset$;
for all slots in descending order of f_j **do**
  gather all C_i whose a_i has the j-th bit on;
  while $(k < \gamma \cdot |\mathbb{C}|)$ AND (there is unprocessed C_i) **do**
    mark a C_i that is not in $|\mathbb{C}_s|$ as $C_{s,i}$;
    insert $C_{s,i}$ into $\mathbb{C}_s$;
    $k = k + 1$;
  end while
  if $k \geq \gamma \cdot |\mathbb{C}|$ **then**
    break;
  end if
end for

Algorithm 3 Defragmentation based Routing and Spectrum Assignment

store current network status in $G'(V', E')$;
release resources assigned to $C_{s,i} \in \mathbb{C}_s$ in G';
for all $C_{s,i} \in \mathbb{C}_s$ in descending order of $sum(a_i)$ **do**
  find K shortest paths for $C_{s,i}$ in G';
  $k = 0$;
  for all routing paths **do**
    if $C_{s,i}$ can be provisioned over this path **then**
      perform spectrum pre-allocation using first-fit;
      record the path's maximum used-slot index after pre-allocation;
      $k = k + 1$;
    end if
  end for
  select the path whose maximum used-slot index is the smallest after pre-allocation;
  store the new RSA in $\{R'_{s,d,i}, a'_i\}$;
  update G' to include the new RSA;
end for

V. Best-Effort Traffic Migration

For each $C_{s,i} \in \mathbb{C}_s$, rerouting needs to accomplish a one-to-one mapping, $M : \{R_{s,d,i}, a_i\} \mapsto \{R'_{s,d,i}, a'_i\}$. For two selected connections C_{s,i_1} and C_{s,i_2}, if the new RSA of C_{s,i_1} requires the resources currently used by C_{s,i_2}, in other words, $R'_{s,d,i_1} \cap R_{s,d,i_2} \neq \emptyset$ and $a'_{i_1} \otimes a_{i_2} \neq 0$, we say that C_{s,i_1} **depends on** C_{s,i_2}. If C_{s,i_1} is rerouted before C_{s,i_2}, there will be traffic disruption since the *make-before-break* scenario [5] is not applicable. The dependency between selected connections can be modeled with a dependency graph. As shown in Fig. 2(a), each selected connection corresponds to a node in the dependency graph, and if C_{s,i_1} depends on C_{s,i_2}, there is a directed link from the node for C_{s,i_1} to that for C_{s,i_2}.

To minimize traffic disruptions, we design a best-effort traffic migration scheme for rerouting and try to apply the *make-before-break* scenario [5] as many as possible. It is known that *make-before-break* can be applicable for all select-

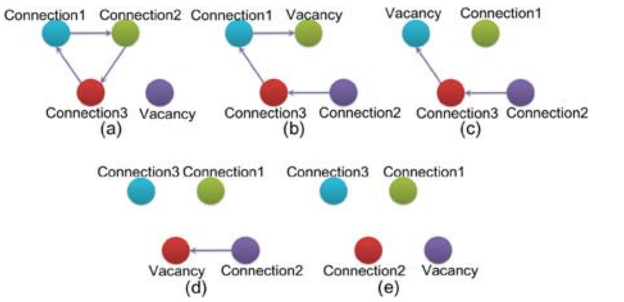

Fig. 2. Traffic migration using the move-to-vacancy (MTV) approach.

ed connections if and only if the dependency graph is acyclic [15]. For the situation in Fig. 2(a), where three connections depend on each other and formulate a cycle, at least one connection has to be stalled during rerouting and hence traffic disruption will occur. To minimize traffic disruptions, we find minimum number of directed links to break in the dependency graph, using an approach developed in [16]. We try to further reduce traffic disruptions with a move-to-vacancy (MTV) approach. Specifically, as shown in Fig. 2(b)-(e), when there is a dependency cycle, we try to find certain resources to set up a connection temporarily, break the cycle, reroute the rest in the cycle, and finally restore the one to its desired RSA. If none of the connections in a cycle can be temporarily rerouted to an alternative RSA, traffic disruption will occur.

VI. Performance Evaluations

We perform simulations with the 14-node NSFNET topology, and assume that the EON is deployed in the C-Band. Hence, each fiber link has $\sim$4.475 THz bandwidth to allocate, which corresponds to 358 12.5-GHz subcarrier slots ($B = 358$). The dynamic connection requests are generated using the Poisson traffic model. For each request C_i, the number of slots is uniformly distributed with in $1 - 16$ and the source-destination pair is randomly chosen. The requests are originally served with the K-shortest paths and balanced load spectrum assignment (KSP-BLSA) algorithm [17]. The threshold for triggering the bandwidth defragmentation, TH, is set as 300. To evaluate the performance of the proposed algorithm, we define two performance metrics as follows:

Definition 1 (Bandwidth Blocking Probability) Bandwidth blocking probability (BBP) is defined as the ratio of blocked connection bandwidth versus total requested bandwidth.

Definition 2 (Bandwidth Fragmentation Ratio) We use bandwidth fragmentation ratio (BFR) to investigate the effectiveness of the defragmentation. We define the BFR of a link e as [18]:

$$\psi_e = \begin{cases} 1 - \frac{MaxBlock(b_e)}{B - sum(b_e)}, & sum(b_e) < B \\ 0, & sum(b_e) = B \end{cases} \quad (2)$$

where $MaxBlock(\cdot)$ returns the maximum size of available slot-blocks in b_e. Then, the network BFR Ψ of the EON is

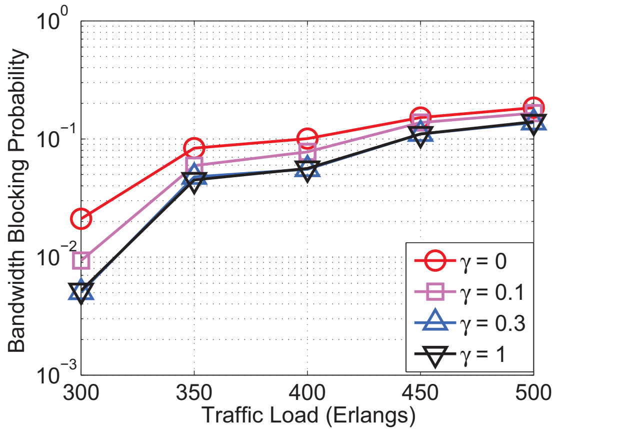

Fig. 3. Bandwidth blocking probability of defragmenation using HUSIF with different γ.

defined as:

$$\Psi = \frac{\sum_{e \in E} (\psi_e)}{|E|} \quad (3)$$

Fig. 3 shows the BBP results from the defragmentation using HUSIF as the selection strategy. As the references, the BBP results from no defragmentation ($\gamma = 0$) and Greenfield defragmentation ($\gamma = 1$) are also plotted. As expected, defragmentation with a larger selection ratio γ results in a lower BBP. However, it is interesting to notice that the BBP curve of HUSIF with $\gamma = 0.3$ is very close to that of $\gamma = 1$ (Greenfield defragmentation). Fig. 4 compares the BBP results from four defragmentation scenarios. The results indicate that the defragmentations using both HUSIF and MFUSF reduce BBP, while they are more effective for a smaller traffic load. As the traffic load increases, the links' spectrum becomes more crowded and leaves smaller space for the defragmentation to operate. The BBP results in Fig. 4 also suggest that HUSIF is a more efficient selection strategy than MFUSF. The traffic disruption percentages are listed in Table I for these four scenarios with and without MTV. When $\gamma = 0.3$, the traffic disruption percentages are less than 1% for defragmentations without MTV. The MTV approach can further decrease the percentages down to within 0.25%.

Fig. 5 illustrates the benefit of defragmentation in terms of network BFR. The traffic load is fixed at 500 Erlangs, and the network BFR is plotted for 50 simulation time points. It can be seen clearly that the defragmentation operations generate dips on the BFR curves. Among the four defragmentation scenarios, the Greenfield one ($\gamma = 1$) achieves the most BFR reduction after each operation. While with $\gamma = 0.3$, the one using HUSIF achieves larger BFR reduction than that using MFUSF.

VII. Conclusion

We proposed a novel comprehensive bandwidth defragmentation algorithm. In order to make the BBP performance comparable with that from the Greenfield scenario (100% rerouting

TABLE I
TRAFFIC DISRUPTION PERCENTAGES FROM DEFRAGMENTATIONS

Traffic Load (Erlangs)	$\gamma = 0$		MFUSF, $\gamma = 0.3$		HUSIF, $\gamma = 0.3$		$\gamma = 1$	
	w/o MTV	$w/$ MTV	w/o MTV	$w/$ MTV	w/o MTV	$w/$ MTV	w/o MTV	$w/$ MTV
300	0	0	0.27%	0.00%	0.30%	0.00%	4.90%	0.00%
350	0	0	0.49%	0.14%	0.60%	0.06%	5.40%	0.46%
400	0	0	0.43%	0.10%	0.55%	0.15%	6.10%	0.52%
450	0	0	0.40%	0.11%	0.93%	0.24%	6.11%	1.73%
500	0	0	0.46%	0.10%	0.62%	0.20%	5.78%	1.66%

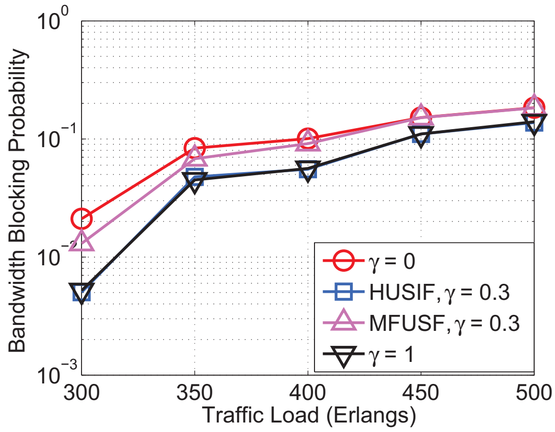

Fig. 4. Bandwidth blocking probability of four defragmenation scenarios

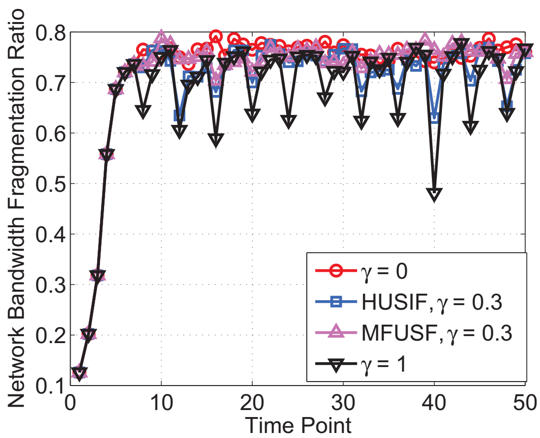

Fig. 5. Network bandwidth fragmentation ratio over simulation time points (traffic load = 500 Erlangs)

all the time), the proposed algorithm only needed to reroute a portion (∼30%) of the existing connections. Our investigations on how to choose the most "critical" connections for rerouting showed that the defragmentation using the HUSIF strategy could achieve better performance in terms of BBP and network BFR reduction, compared to that using MFUSF. Simulation results demonstrated that the traffic disruption percentages were less than 1% for defragmentations with 30% rerouting, and they could be further reduced to within 0.25% by adding the MTV approach in traffic migration.

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