Planning and Provisioning of Elastic O-OFDM Networks with Fragmentation-Aware Routing and Spectrum Assignment (RSA) Algorithms

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Abstract: We formulate fragmentation ratio to quantify bandwidth fragmentation, and propose two fragmentation-aware RSA algorithms to alleviating it in both static planning and dynamic provisioning of O-OFDM networks. Simulation results indicate that the proposed RSA algorithms outperform two existing ones.
OCIS codes: (060.4251) Networks, assignment and routing algorithm; (060.4264) Networks, wavelength assignment

1. Introduction

Optical orthogonal frequency-division multiplexing (O-OFDM) [1] achieves sub-wavelength granularity by using elastic bandwidth allocation that manipulates subcarrier frequency slots. However, as the granularity of bandwidth allocation gets smaller, bandwidth fragmentation can become a serious issue when connections are set up and torn down dynamically and the spectrum resource is splintered into blocks with small bandwidths. In [2], the authors proposed to use the utilization entropy (UE) to quantify bandwidth fragmentation. However, as we will show later, UE may not be able to precisely describe bandwidth fragmentation in certain scenarios. In this paper, we start with formulating proper and scientific metric to quantify bandwidth fragmentation, and then use it to design network control mechanisms that can reduce or avoid fragmentation. The metric, called as fragmentation ratio (FR), can measure the contiguousness of available frequency slots along a routing path. Based on it, we propose two routing and spectrum assignment (RSA) algorithms to alleviate bandwidth fragmentation in O-OFDM networks. Simulation results indicate that the proposed algorithms can effectively alleviate bandwidth fragmentation in both static network planning and dynamic network provisioning, and outperform the existing RSA algorithms.

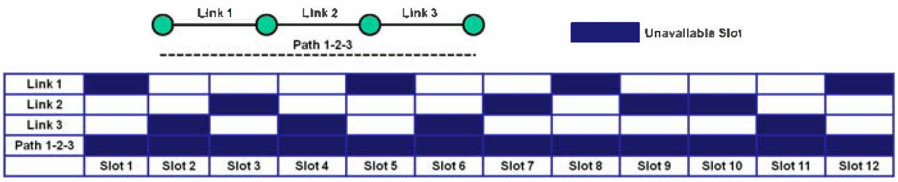

Fig. 1 An example of bandwidth fragmentation

2. Fragmentation Ratio Formulations

Fig. 1 shows an example of bandwidth fragmentation in elastic O-OFDM networks. Based on spectrum utilization of its three links, we obtain slot-availability of the path. It can be seen that even though the utilization is only 33%, there is no available slot on the path and all requests that try to use it will be blocked. Fig. 1 also shows that the fragmentation here has similarities with that in storage systems, such as hard-disks. Hence, by borrowing the definitions for storage systems [3,4], we obtain the fragmentation ratio (FR) to quantify bandwidth fragmentation of a link or a path as

$$FR = 1 - \frac{\sum_i f_i^p}{(\sum_i f_i)^p} \tag{1}$$

where i is the index of available slot-blocks (i.e., block of contiguous slots), f_i is the size of the available slot-block, and p is a constant. Bandwidth blocking probability (BBP), defined as the ratio of blocked connection bandwidth vs. total requested bandwidth, is a metric for assessing the performance of network planning and provisioning algorithms. From the example in Fig. 1, we can see that both spectrum utilization and bandwidth fragmentation can affect BBP of O-OFDM networks. Therefore, we expect that when spectrum utilization and requested bandwidth distribution are fixed, a well-defined FR should have a clear mapping between it and BBP. When the definition of

FR is determined, we should be able to use it together with spectrum utilization to estimate BBP and tell when defragmentation is necessary.

We design simulations to investigate BBP's relationship between FR and spectrum utilization. Using the 14-node NSFNET topology, we assume that each fiber link has a capacity of 5 THz and the bandwidth of each slot is 12.5 GHz. After selecting a fixed utilization value, we vary the number of available slot-blocks in network to control the FR. The available slot-blocks, whose sizes follow a normal distribution, are distributed randomly on each link along the spectrum space. After a synthetic network scenario is created with a certain FR. a new request arrives with a random *s-d* pair ($s, d \in V$) and the requested bandwidth follows uniform distribution in [25, 500] GHz. If it cannot be served with the shortest routing path, it is blocked. The network is restored to the original status afterwards. Without loss of generality, the BBP is calculated by randomly generating 10,000 requests and repeating above procedures. Fig. 2 shows the simulation results. We calculate the proposed FR with p=1.5 and 2 respectively, and compare it the UE in [2]. It can be seen that the results of FR with p=1.5 and 2 reveals a more proportional relationship between it and BBP, while the relationship between UE and BBP is more likely to be unpredictable, which undermines its significance of quantifying fragmentation in a network. Moreover, UE covers the smallest range in [0,1], which disqualifies itself to be a unified parameter. Therefore, the FR definition in Eqn. (1) achieves better representation of bandwidth fragmentation than UE and makes it easier to help predicting the BBP in a network.

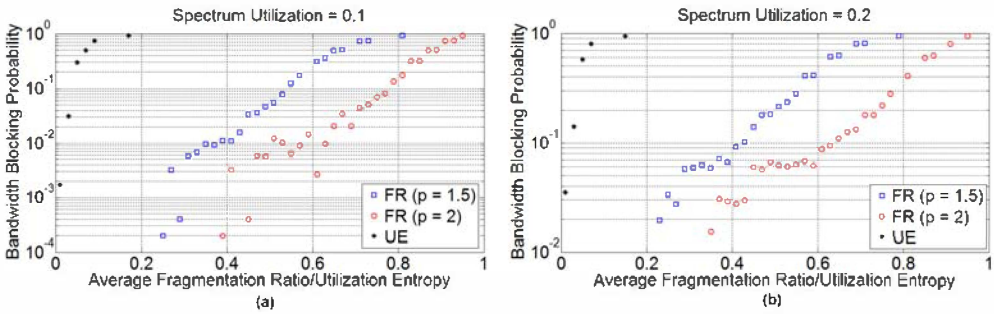

Fig. 2 Bandwidth blocking probability (BBP) vs. fragmentation ratio (FR)/Utilization Entropy (UE)

3. Fragmentation-Aware RSA Algorithms

With a properly defined FR, we can use it as a metric in RSA to alleviate bandwidth fragmentation in both static network planning and dynamic network provisioning. In this section, we discuss two RSA algorithms that can control the increase of FR and reduce necessary defragmentation operations in networks. Consider the physical network topology as *G(V, E)*, where *V* is the node set, and *E* is the fiber link set. For a lightpath request $L_{s,d}$ that is from node *s* to node *d*, we calculate all possible routing paths and store them in the available path set $A_{s,d}$. Then, for each path in $A_{s,d}$, we apply a prejudgment procedure. For a link $e \in E$, we assume the maximum index of its used slots is M_e, according to the current spectrum utilization. Then, for a routing path $r_{s,d}$ that consists of multiple links, the maximum index of used slots on it is $\max(M_e), \forall e \in r_{s,d}$. The prejudgment procedure tries to accommodate $L_{s,d}$ with each path in $A_{s,d}$ using the first-fit scheme. If the maximum index of used slots on the path is unchanged after serving $L_{s,d}$, we put the path in the candidate path set $R_{s,d}$. For each link $e \in E$, we define a bit-mask $b_e[1...B]$ and use it for spectrum assignment, where *B* is the total number of slots on a link in the network. Here, if the *j*-th slot on link *e* is available, $b_e[j]=1$; otherwise, $b_e[j]=0$. The proposed fragmentation-aware RSA employs two mechanisms to finalize the resource allocation of $L_{s,d}$:

1) The minimum network fragmentation ratio RSA (MNFR-RSA) algorithm makes resource allocation based on the network fragmentation ratio (NFR) defined as:

$$NFR = \frac{\sum_{e \in E} FR_e}{|E|} \tag{3}$$

where FR_e is the FR of link *e*, and $|E|$ is the total number of links in *G(V, E)*. MNFR-RSA chooses a path from $R_{s,d}$ that can achieve the minimum NFR to serve $L_{s,d}$. If $R_{s,d}$ is empty, in static planning MNFR-RSA accommodates $L_{s,d}$ with the path that has the minimal distance in $A_{s,d}$ and in dynamic provisioning $L_{s,d}$ is blocked.

2) The maximum local utilization RSA (MLU-RSA) algorithm alleviates bandwidth fragmentation by utilizing the slots that have already been used the most in the network. Specifically, if $L_{s,d}$ requests *C* slots and to

accommodate it with path $r_{s,d} \in A_{s,d}$, we need to allocate slots starting from index I, we define the local utilization (LU) on $r_{s,d}$ after accommodating $L_{s,d}$ as:

$$LU = 1 - \frac{\sum_{e \in E} \sum_{j=I}^{I+C-1} b_e[j]}{|E| \cdot C} \qquad (2)$$

Then, the MLU-RSA algorithm chooses the path with the maximal LU from $R_{s,d}$ to serve $L_{s,d}$. When $R_{s,d}$ is empty, the handling of $L_{s,d}$ is the same as that in MNFR-RSA.

In order to evaluate the performance of the proposed RSA algorithms, we perform simulations for both static network planning and dynamic network provisioning with the NSFNET topology. The assumptions on fiber capacity and subcarrier slot bandwidth are the same as those in the previous section. The *s*-*d* pair of each $L_{s,d}$ is randomly chosen and the requested number of slots varies uniformly with in [1, 10]. In both static and dynamic simulations, we compare our algorithms with two existing ones, the shortest-path first-fit RSA (SPFF-RSA) [5], and the K shortest-path balanced-load spectrum assignment (KSP-BLSA) [6]. Fig. 3 shows the results comparison for static network planning. It can be see that the proposed algorithms outperforms the existing algorithms in terms of both the maximum used slot index and network fragmentation ratio (NFR). Between the two proposed algorithms, their performance on the maximum used slot index is similar, while MNFR-RSA provides smaller NFR when the number of requests is the same. Fig. 4 shows the results comparison for dynamic network provisioning. It can be see that both proposed algorithm outperform the existing algorithm in terms of BBP. While for the NFR comparison, SPFF-RSA achieves the lowest NFR even through its BBP is the highest. This is due to the reason that the FR calculation in Eqn. (1) only consider the link dimension, but does not consider the slot misalignment in the path dimension. We will investigate FR of path dimension in future works.

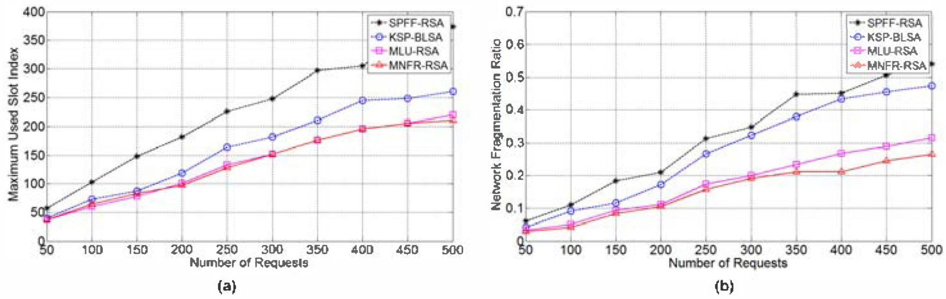

Fig. 3 Simulation results for static network planning: a) maximum used slot index, and b) network fragmentation ratio (NFR)

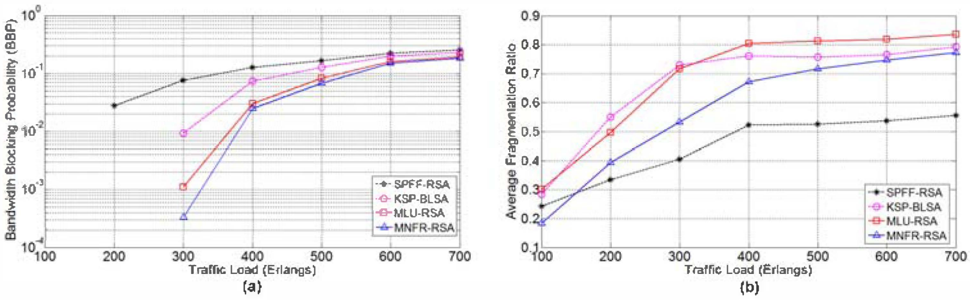

Fig. 4 Simulation results for dynamic network provisioning: a) bandwidth blocking probability (BBP), and b) network fragmentation ratio (NFR)

4. Summary

We formulated fragmentation ratio to quantify bandwidth fragmentation, and proposed two fragmentation-aware RSA algorithms to alleviating it in both static planning and dynamic provisioning of O-OFDM networks. Simulation results indicated that the proposed RSA algorithms outperformed two existing ones, the SPFF-RSA and KSP-BLSA.

5. References

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