Spectrum consecutiveness based routing and spectrum allocation in flexible bandwidth networks

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In flexible bandwidth optical networks, the dynamic lightpath setup and teardown inevitably lead to spectrum fragmentation which blocks the new connections. In order to effectively allocate the spectrum along a better route, a notion of available spectrum consecutiveness is introduced and three dynamic routing and spectrum assignment (RSA) algorithms are proposed in this letter accordingly. The novel algorithms retain the spectrum consecutiveness as much as possible when establishing a lightpath and reduce the spectrum fragmentation. Simulation results indicate that our proposed spectrum consecutiveness based RSA algorithms achieve lower blocking probability and higher adaptability to more line rates mixture.

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Due to the increasing demands for bandwidth and the limited number of wavelengths per fiber, spectrum efficiency has become the target parameter for improvement in backbone networks. The traditional optical transport networks, which strictly follow the ITU-T wavelength grids and spacing, lead to low optical spectrum utilization. Moreover, another problem seemed to be more significant when traffic demand needed multiple wavelengths, for it cannot eliminate the spectral gap between any two wavelengths. To better utilize the frequency resource and accommodate the super-wavelength traffic effectively, a novel flexible bandwidth optical network[1−3] has been proposed and demonstrated. The enabling technologies, such as OFDM[4,5] based bandwidth-variable transponder (BV-Transponder) and BV-WXC had turned the flexible bandwidth optical network into reality[6,7]. In such a flexible architecture, the optic fiber spectrum is further divided into a number of narrow frequency segments, which are named as frequency slots (FSs). According to the request bandwidth and the modulation format, an optical path is established by assigning a certain number of contiguous FSs, taking the guard band into consideration.

Analogizing to the routing and wavelength assignment (RWA) issue in traditional network scenario, the routing and spectrum assignment (RSA) issue emerges and becomes a key technology in this novel network. During the RSA computation process, there are three kinds of constraints: 1) spectrum continuity constraint which means allocating the same spectral resources on each link along the route of a channel, 2) spectrum contiguity (or adjacency) constraint which ensures subcarriers to be adjacent to each other in one channel, and 3) the spectral conflict constraint, which is defined as non-overlapping spectrum allocation to different channels on the same fiber. These constraints make RSA computation different and more challenging. There have been a few studies focusing on the RSA computation, which can be broadly classified into static, incremental and dynamic path provisioning[8]. The static RSA problem is proved to be NP-complete and its metric is frequency utilization efficiency[9−11]. Regarding the incremental provisioning, a RSA algorithm for flexible bandwidth optical networks was first presented in Ref. [12] where a permanent path was provisioned on a one-by-one basis and the RSA algorithm was a simple first-fit (FF) algorithm. As for the dynamic RSA problem[13−15], the frequency resources could suffer from fragmentation over time where there were no enough large blocks of free spectrum to provide for higher bandwidth services. It is for this reason that the dynamic RSA issue concerns more about the blocking probability mainly caused by the spectrum fragmentations.

In this letter, a notion of available spectrum consecutiveness, which indicates the spectrum occupation in the network is introduced. Accordingly, three dynamic RSA algorithms are proposed. They are maximize path spectrum consecutiveness (MPSC) algorithm, maximize total link spectrum consecutiveness (MTLSC) algorithm, and maximize heaviest link spectrum consecutiveness (MHLSC) algorithm. We apply these three algorithms to dynamic provisioning and the results show that they are most efficient in terms of blocking probability among the evaluated algorithms.

Define a network as $G\{V, E, S\}$, where V represents the set of BV-switching nodes, E represents the set of bi-directional fiber links between nodes in V. Let $|V| = N$ and $|E| = L$ denote the number of network nodes and links, respectively. S denotes the set of frequency slots on each fiber link, $|S| = F$. The spectrum occupation on a link is expressed by a F bits array $U_{\rm l} = [u_1^{\rm l}, u_2^{\rm l}, \ldots, u_F^{\rm l}]$, in which each binary bit indicates the usage condition of the corresponding frequency slot on the link. The bit value 1 means a free slot while the bit value 0 corresponds to an occupied slot. The spectrum occupation along a path is calculated as

$$U_{\rm p} = \bigcap_{l\in L(s,d)} U_{\rm l} = [u_1^{\rm p}, u_2^{\rm p}, \ldots, u_F^{\rm p}], \qquad (1)$$

where $L(s,d)$ is the link set of the path p.

In order to describe the spectrum fragmentation in a link or along a path, we introduce a notion named available spectrum consecutiveness, abbreviates as spectrum consecutiveness. Based on this notion, the link spectrum consecutiveness ($C_{\rm l}$) and path spectrum consecutiveness ($C_{\rm p}$) are defined as

$$C_{\rm l}=\frac{\sum\limits_{i=1}^{\rm F-1} u_i^{\rm l}\cdot u_{i+1}^{\rm l}}{B_{\rm l}}\times\frac{\sum\limits_{i=1}^{F} u_i^{\rm l}}{F} \text{ and } C_{\rm p}=\frac{\sum\limits_{i=1}^{F-1} u_i^{\rm p}\cdot u_{i+1}^{\rm p}}{B_{\rm p}}\times\frac{\sum\limits_{i=1}^{F} u_i^{\rm p}}{F}. \quad (2)$$

Here, there are $B_{\rm l}$ available spectral blocks in link l and according to the spectrum occupation array $U_{\rm p}$, the path p contains $B_{\rm p}$ free spectra blocks.

The value of $C_{\rm l}$ and $C_{\rm p}$ represent the possibility that the vacant spectral resources could be used. They reflect two key general points. The first point is the percentage of available frequency slots in the link or along the path, which are represented by $\sum\limits_{i=1}^{F} u_i^{\rm l}\Big/F$ and $\sum\limits_{i=1}^{F} u_i^{\rm p}\Big/F$. If there are more available FSs, the value of them are larger. It means the path or the link with more FSs has a higher probability to avoid blocking and can more easily use the contiguous slots for the end-to-end route. Secondly, they reflect the consecutiveness of the available slots in the link or along the path, which is specific to the flexible bandwidth optical networks. Take $C_{\rm l}$ for example, $\sum\limits_{i=1}^{F-1} u_i^{\rm l}\cdot u_{i+1}^{\rm l}$denotes the total joint numbers between free FSs in the frequency resource pool and the value $\sum\limits_{i=1}^{F-1} u_i^{\rm l}\cdot u_{i+1}^{\rm l}\Big/B_{\rm l}$ reflects average joint numbers in each free spectral block on the link. The link with more contiguous available slots should have a higher value than slots sparsely distributed on the frequency axis.

Figure 1 is an example of calculating link spectrum consecutiveness. Take L1 for example, there are 16 free FSs and the total joint number between them is 6; the number of available spectral blocks is 2 and the number of FS is 16; so the link spectrum consecutiveness of L1 is 1.5. In the same way, the link spectrum consecutivenesses of L2 and L3 are 0.9375 and 1.833, respectively.

In flexible bandwidth optical networks, the dynamic lightpath setup and teardown will inevitably cause spectrum fragmentation which new arrival connections have to reuse. In order to effectively allocate the spectrum along a better route, we propose three dynamic RSA algorithms based on the notion of spectrum consecutiveness, i.e. MPSC, MTLSC, and MHLSC. The aim of these algorithms is to minimize the blocking probability by means of maximizing available spectrum consecutiveness.

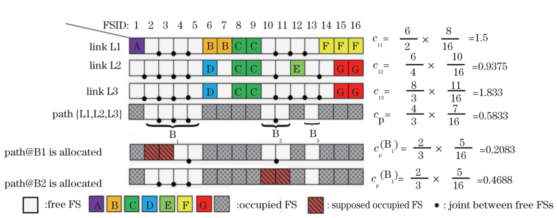

Fig. 1. Example of link spectrum consecutiveness.

Here we define the bandwidth of each frequency slot as 12.5 GHz. Then serving a connection requiring T subcarriers is translated into finding a free spectral block which contains at least T contiguous frequency slots. The guard band frequency is out scope of this letter. In addition, for the source node s and destination node d, $L(s,d)=\{l_1,l_2,\ldots,l_n\}$ is the link set of path p.

In the MPSC algorithm, the KSP algorithm is applied to calculate k-shortest-paths as candidates from source s to destination d. Then for the candidate path p, the spectrum occupation along it is calculated by Eq. (1). According to the spectrum occupation array $U_{\rm p}$, from the beginning bit to the end, it searches for the available consecutive slots (i.e., spectral blocks) which can accommodate the traffic demand as candidate block set (say $B_{\rm p}=\{B_1,B_2,\ldots,B_n\}$). For each candidate block B_i, assuming that the consecutive slots in the lower end of the current candidate block are allocated, the path spectrum consecutiveness ($C_{\rm p}^{(B_i)}$) is calculate by Eq. (2). Then this result is recorded in the set $C_p=\{C_p^{B(1)},\ldots,C_p^{B(i)},\ldots,C_p^{B(n)}\}$. Finally, the block B_i which has the biggest value of $C_{\rm p}^{(B_i)}$is selected.

For example in Fig. 1, there arrives a connection request which needs two consecutive slots, $B_{\rm p}=\{B_1,B_2\}$ is found by the bitwise OR operation of link spectrum usage along the path. For the candidate spectrum block B_1, assuming that No. 2 and No. 3 slots are allocated, path spectrum consecutiveness ($C_{\rm p}^{(B_1)}$) is calculated by Eq. (2) and recorded in the set $C_{\rm p}=\{C_{\rm p}^{B(1)},C_{\rm p}^{B(2)}\}$. So similarly, for the candidate spectrum block B_2, assuming that No. 10 and No. 11 slots are occupied, path spectrum consecutiveness ($C_{\rm p}^{(B_2)}$) is calculated and recorded. In this example $C_{\rm p}^{(B_1)}=0.2083$ and $C_{\rm p}^{(B_2)}=0.4688$, so B_2 is selected and No. 10 and No. 11 slots are allocated.

The procedure of MPSC algorithm is as follows:

Algorithm 1: MIPSC

1) use KSP algorithm to calculate k-shortest-paths as candidates from source to destination

2) **while** there exists non-zero candidate path ($k>0$) **do**

3) calculate the path spectrum occupation by Eq. (1);

4) search for the available spectral blocks as candidate block set which can accommodate the traffic demand (say $B_{\rm p}=\{B_1,B_2,\ldots,B_n\}$);

5) **for** every candidate spectrum block B_i ($0<i<n$) **do**

6) calculate the path spectrum consecutiveness ($C_{\rm p}^{(B_i)}$) by Eq. (2), assuming that the first available consecutive slots in the current candidate block are allocated;

7) record the result in the set $C_{\rm p}=\{C_{\rm p}^{B(1)},\ldots,C_{\rm p}^{B(i)},\ldots,C_{\rm p}^{B(n)}\}$;

8) **end for**

9) select the block B_i which $C_{\rm p}^{B(i)}=\max_{\forall j}C_{\rm p}^{B(j)}$; allocate the available consecutive slots in the lower end of the block to the traffic demand;

10) **end while**.

MTLSC algorithm and MHLSC algorithm use the same method to find the candidate spectral blocks as the MPSC algorithm. In particular, the MTLSC algorithm evaluates the sum of spectrum consecutiveness on all links along the path and selects the block with the maximum value. The MHLSC algorithm is designed considering the spectrum consecutiveness of the heaviest payload link: the block which can maximize the heaviest payload link consecutiveness is chosen. The procedures of MTLSC algorithm and MHLSC algorithm are as follows:

Algorithm 2: MTLSC
1) Use KSP algorithm to calculate k-shortest-paths as candidates from source to destination
2) **while** there exists non-zero candidate path ($k > 0$) **do**
3) calculate the path spectrum occupation by Eq. (1);
4) search for the available spectral blocks as candidate block set which can accommodate the traffic demand (say $B_{\rm p} = \{B_1, B_2, \ldots, B_n\}$);
5) **for** every candidate spectrum block B_i ($0 < i < n$) **do**
6) **for** every link $l_i \in L(s,d)$ **do**
7) calculate the link spectrum consecutiveness ($C_{l_i}^{(B_i)}$) by Eq. (2), assuming that the first available consecutive slots in the current candidate block are allocated on that link;
8) $C_{\rm l}^{B(i)} \leftarrow C_{\rm l}^{B(i)} + C_{l_i}^{B(i)}$
9) **end for**
10) record the result in the set $C_{\rm l} = \{C_{\rm l}^{B(1)}, ..., C_{\rm l}^{B(i)}, ..., C_{\rm l}^{B(n)}\}$;
11) **end for**
12) Select the block B_i which $C_{\rm l}^{B(i)} = \max_{\forall j} C_{\rm l}^{B(j)}$; allocate the available consecutive slots in the lower end of the block to the traffic demand;
13) **end while**.

Algorithm 3: MHLSC
1) Use KSP algorithm to calculate k-shortest-paths as candidates from source to destination.
2) **while** there exists non-zero candidate path ($k > 0$) **do**
3) calculate the path spectrum occupation by Eq. (1);
4) search for the available spectral blocks as candidate block set which can accommodate the traffic demand (say $B_{\rm p} = \{B_1, B_2, \ldots, B_n\}$);
5) **for** every candidate spectrum block B_i ($0 < i < n$) **do**
6) select the link $l \in L(s,d)$ that has the heaviest pay load;
7) calculate the link spectrum consecutiveness ($C_{l}^{(B_i)}$) by Eq. (2), assuming that the first available consecutive slots in the current candidate block are allocated on that link;
8) record the result in the set $C_{\rm l} = \{C_{\rm l}^{B(1)}, \ldots, C_{\rm l}^{B(i)}, \ldots, C_{\rm l}^{B(n)}\}$;
9) **end for**
10) select the block B_i which $C_{\rm l}^{B(i)} = \max_{\forall j} C_{\rm l}^{B(j)}$; allocate the available consecutive slots in the lower end of the block to the traffic demand;
11) **end while**.

Simulations are conducted to evaluate our proposed RSA algorithms based on OMNet++ simulator. The widely-used NSFNet (14 nodes, 21 links) and ARPA-2 (21 nodes, 24 links) networks are used as the simulation topologies (as shown in Fig. 2). The overall spectrum of each fiber link is 4 400 GHz, which can carry 352 slots in the flexible bandwidth network with 12.5-GHz slot bandwidth. The traffic connection requests for each node pairs are distributed randomly over the network spatially and for temporal distribution, they follow as a Poisson process with an arrival rate λ (call/s). The holding time of each call is exponentially distributed with mean value μ. The network support five types of connection line rates, which are 10, 40, 100, 400, and 1 000 Gb/s. Note the actual transmitting spectrum is dependent on various factors such as modulation type, network and hardware conditions. Here for simulation purpose, we neglect these influence and suppose that the required spectrums for each line rate are 25, 50, 50, 75[16], and 150 GHz[7] and the required FS number s are 2, 4, 4, 6, and 12, respectively.

For comparison purpose, besides three spectrum consecutiveness based RSA algorithms, three other RSA algorithms are evaluated as well:

(1) WDM based RWA algorithm: 10, 40, and 100 Gb/s signals are carried by one wavelength. 400 Gb/s and 1 Tb/s are carried by 4 and 10 inverse-multiple wavelength, i.e., the wavelengths need not to be contiguous. The shortest path algorithm is applied for route computation and FF scheme is for the wavelength assignment. The connection is blocked if the required number of wavelengths cannot be found.

(2) KSP based RSA algorithm[15]: The KSP algorithm is used to calculate k-shortest-paths. Along the ith shortest path, the FF algorithm searches for available frequency slots from the lowest slot ID until the required number of contiguous slots are found.

Random-fit (RF) algorithm: The KSP algorithm is used to calculate k-shortest-paths. Along the ith shortest path, the contiguous slots are selected by random decision.

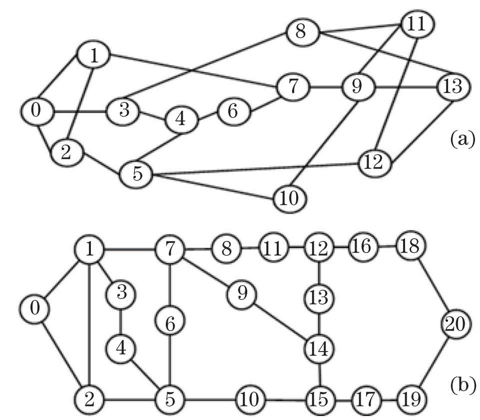

Fig. 2. Network topology in simulation. (a) NSFNet topolgy, node=14, link=21; (b) ARPA-2 topology, node=21, link=26.

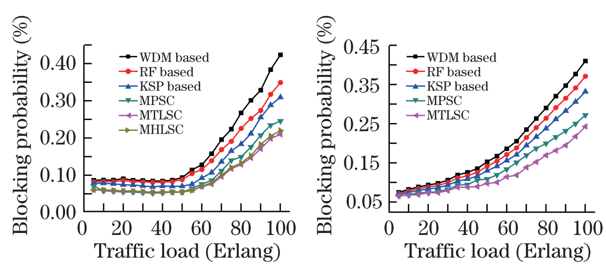

Fig. 3. Blocking probability of six strategies with three line rates on (a) NSFNet and (b) ARPA-2.

Firstly, three types of demands, 40, 100, and 400 Gbps, are generated with equal probability, i.e. 33% each. The comparisons on blocking probability among these six algorithms in two different topologies are shown in Fig. 3. As shown, in both scenarios, three spectrum consecutiveness based RSA algorithms lead to much lower blocking probability than the other three algorithms. The reason for this is that the proposed algorithms retain the spectrum consecutiveness as much as possible when allocating the spectrum resources, thus reuse the fragments on the link or along the path at large. However, without consideration of spectrum consecutiveness, RF and FF based algorithms tend to bring out more spectrum fragments, thus blocking the following connections. Other phenomenon can be observed is that compared among three proposed algorithms, both MTLSC algorithm and MHLSC algorithm achieve better performance than MPSC algorithm. This is because MPSC algorithm maximizes the value of C_{p} which is calculated by the bitwise OR operation of link spectrum usage along the path. From this statistical point of view, MPSC does not concern about the detail links spectrum consecutiveness. However, MTLSC and MHLSC allocate spectrum on the link perspective, which achieve better performance.

For further comparison, the types of connection line rates are added from 3 to 5, i.e., 10, 40, 100, 400, and 1 000 Gbps are generated with equal probability. Then we evaluate the performance of these RSA algorithms in the same test settings. The results are shown in Fig. 4. One can see that the proposed algorithms still outperform the other three algorithms in both network topologies. It is also observed that the blocking probability of all algorithms degrades by adding the type of line rate, as shown in Fig. 5. The reason is that in dynamic traffic scenario, more types of line rates lead to more spectrum fragments, thus further decreasing the probability of finding sufficient contiguous spectrum for a connection. However, the deterioration degrees of three spectrum consecutiveness based algorithms are more slightly than the others. This result indicates in case of more line rates mixture, the spectrum consecutiveness based RSA algorithms present highly adaptability than the other strategies.

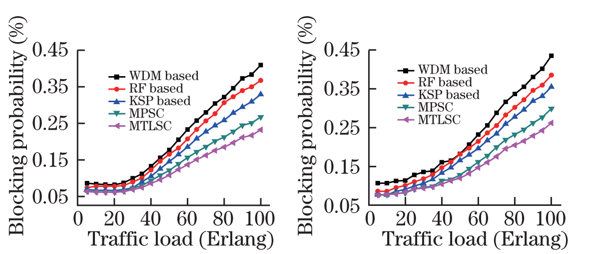

Fig. 4. Blocking probability of five strategies with five line rates on (a) NSFNet and (b) ARPA-2.

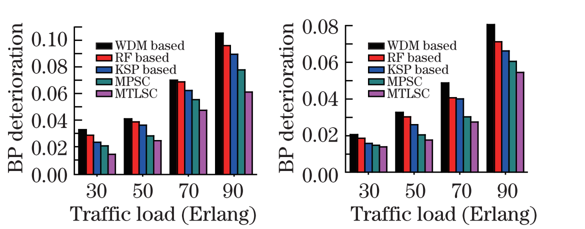

Fig. 5. Blocking probability deterioration by adding line rates on (a) NSFNet and (b) ARPA-2.

In conclusion, flexible bandwidth optical network is receiving recent attention as a spectrum-efficient architecture that can offer flexible and elastic band-width allocation. In this letter, aiming at dynamic RSA problem, we introduce a notion of available spectrum consecutiveness and propose three heuristic RSA algorithms based on it. An advantage of our algorithms is that they retain the spectrum consecutiveness as much as possible when establishing a lightpath. In this way, the spectral fragments are reused effectively. Simulation results indicate that our proposed RSA algorithms achieve lower blocking probability and higher adaptability to more line rates mixture.

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