Spectral and Spatial 2D Fragmentation-Aware Routing and Spectrum Assignment Algorithms in Elastic Optical Networks [Invited]

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***Abstract*—This paper investigates the spectrum fragmentation issue, which undermines the bandwidth efficiency in elastic optical networks. After categorizing the two-dimensional fragmentation problem as the fragmentation and misalignment subproblems, this paper proposes joint routing and spectrum assignment (RSA) algorithms to alleviate the spectral fragmentation in the lightpath provisioning process. The time complexity of the two proposed algorithms are analyzed in detail, and both algorithms can run in $O(kdnC \log C)$ time, where k is the number of the shortest path in the routing algorithm, d is the maximum node degree in the network, n is the number of nodes in the network, and C is the link capacity expressed as the number of spectral slots. Simulation results indicate that the proposed fragmentation-aware (FA) RSA algorithm and the FA algorithm with congestion avoidance (CA) outperform the existing schemes in terms of blocking probability (BP) reduction. Compared with the benchmark K-shortest-path routing and first-fit assignment (KSP-FF) algorithm, the proposed FA and FA-CA algorithms can achieve a BP reduction of [100%, 4.43%] and [100%, 6.45%], respectively, according to the traffic load in a sample NSFNET topology.**

***Index Terms*—Algorithm; Elastic optical networking; Routing and spectrum assignment; Spectrum fragmentation.**

I. Introduction

Elastic optical networking (EON) is a new network paradigm driven by the increasingly diversified traffic demands and the ever changing traffic patterns over the Internet [1,2]. When the rigid spectral grid in a typical wavelength division multiplexing (WDM) network is replaced with a flexible grid, each channel can span the appropriate amount of spectrum that closely matches the actual demand. While the flexible grid can ultimately become gridless for maximum flexibility, currently it is more common to achieve flexibility by defining small spectrum granularity and assigning an integer number of slots to the demands [3]. However, as the granularity of bandwidth allocation becomes finer, an incoming connection may request a large number of spectral slots that need to be allocated tightly together to maintain high spectral efficiency. This flexibility and high spectral efficiency introduces the difference between EON and the traditional WDM networks. Even if traditional WDM networks can achieve super-high-bandwidth channels through inverse multiplexing where each channel uses on-grid discrete wavelengths, the achievable spectral efficiency is much lower than in the case of EON. However, since EON allows connections to be assigned with nonuniform spectral resources, it will fragment the spectrum, leaving small blocks of spectrum slots useless to bulky requests. This fragmentation will eventually lead to poor spectrum utilization and a high blocking ratio.

Fragmentation in computer memories and storage modules is a well-known problem [4]. However, the fragmentation problem in EON is more complicated, since it evolves in two dimensions, i.e., in the spectral and spatial domains. There are a few previous investigations that addressed the problem of fragmentation in EON [5–7], but none of them considered fragmentation in two dimensions. Defragmentation schemes, which reactively reconfigure the spectrum after it is fragmented, have attracted a lot of attention [8–11]. However, it is always beneficial to predefragment the spectrum when a new connection is set up; for example, the routing and spectrum assignment (RSA) process takes the factor of spectrum fragmentation into account and selects the route and spectrum assignments to prevent such a problem. Reference [12] considered fragmentation while performing RSA; however, it dealt only with the fragmentation between the candidate links and their neighboring links. Also, the time complexity of the algorithms was high. For each candidate fiber link and its neighbors, the evaluation function [12] had to run before and after each potential spectrum assignment (the total number of candidates was large), and all the evaluation values had to be collected and compared to choose the best candidate.

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On the other hand, the spectrum continuity constraint (analogous to the wavelength continuity constraint in WDM networks) introduces the spectral alignment problem into EON. More specifically, if a new connection with requests for n slots is provisioned at the available slots $1-n$ on any of the links along a route, then it must be provisioned at slots $1-n$ on all of the other links along the route. If the available pieces of spectral resources are not aligned in any of the links, e.g., link 3 has an available slot range of $3-(n+3)$, then the request will be blocked. Although spectrum conversion technologies (O/E/O, semiconductor amplifiers, tunable lasers, etc. [13]) can relax the spectrum continuity constraint, they significantly add extra costs in hardware and operations. The alignment property makes a good analogy to the TDM-based SONET/SDH [14], where STS-*Nc* (concatenated synchronous transport signal level N) circuits need to be aligned while being assigned time slots. However, unlike the alignment property imposed by the SONET, namely, that a STS-*Nc* circuit can use only slots s to $(s+n-1)$ such that $s \equiv 1 (\mathrm{mod}\ n)$, elastic optical networks allow a "flex-circuit" to start at any available slot position, which provides more flexibility in manipulating the limited spectral resources at the cost of increased spectrum management complexity.

In this paper, we investigate both the fragmentation problem and alignment property in EON. We propose two joint RSA algorithms and compare their performance against existing algorithms [1,15]. The time complexity analysis of the proposed algorithms is presented in detail. Simulations verify the efficiency of the proposed algorithms in terms of blocking probability (BP) reduction.

The remainder of the paper is organized as follows. Section II overviews the related work and analyzes the fragmentation and misalignment problems in EON. In Section III, we propose the fragmentation- and misalignment-aware RSA algorithms and evaluate their performance in terms of BP. All results and analyses are compared with existing RSA algorithms. Section IV concludes this paper.

II. Problem Definition

Fragmentation is a well-studied problem in computing systems [4]. Before paging schemes came into use, the memory systems had to fit an entire program into contiguous memory blocks, a process that was frequently blocked because of the fragmented resources. However, the fragmentation problem in EON has two dimensions, namely, those of *spectral fragmentation* and *spatial fragmentation*. Taking an example network as shown in Fig. 1(a), the vertical dashed outline in Fig. 1(b) indicates the fragmented spectrum resources in link *AB*, which is the fragmentation in the spectral dimension. On the other hand, the horizontal dashed rectangle in Fig. 1(c) indicates the spatial dimension fragmentation, which is essentially the set of usable but misaligned spectrum slots in the neighboring links. We should consider both the spectral and the spatial dimensions when designing solutions to the fragmentation problem. In Figs. 1(a), 1(b), and 1(c), respectively, the

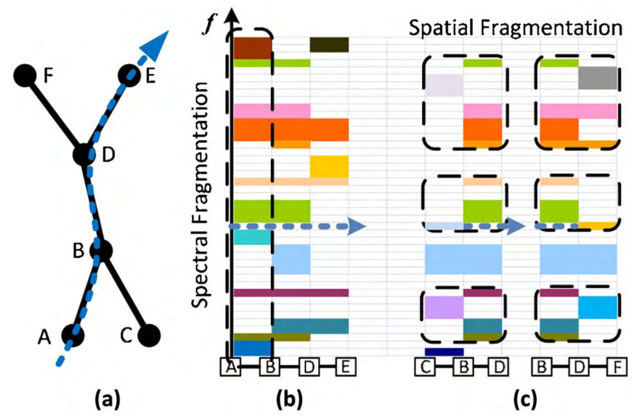

Fig. 1. (a) Sample network and the spectral fragmentation shown in the dashed outline in (b), (b) the spectral dimension on a link, and (c) the spatial dimension on neighboring links.

dashed arrow is the new incoming connection from A to E with the bandwidth requirement of one slot. Apparently, the depicted spectrum assignment not only fills up the fragmented slot on the candidate route *ABDE*, but also fixes the misalignment problem between the candidate link *BD* and its neighboring links *CB* and *DF*. The only negative effect of this RSA is that it fragments the existing continuous big spectrum block on link *DE* (breaking the continuousness of that spectral block). Therefore, an optimized RSA algorithm should assign a new connection in such a way that it fragments the least number of continuous spectral blocks on candidate links, while it fills up as many misaligned spectral slots as possible on neighboring links. Note that the misalignment exists not only between the candidate links and their neighboring links, but also between any link pairs in the network. However, we consider the neighboring links more likely to be routed on one end-to-end path. Therefore, misalignments between neighboring links will most probably increase the end-to-end BP. Note that this is under the assumption of not using any wavelength converters and/or regenerators in the network. For the same reason, [12] also considers only the neighboring links, although its evaluation function can actually run between any link pairs.

Figure 2 shows a more detailed example of the effect on the spectral and spatial fragments before and after a lightpath provisioning process. Suppose that we have a 6-node, 8-link mesh network and that the spectral resources are distributed as shown in Fig. 2(a). For simplicity, in this example we assume only 12 spectrum slots on each fiber link. When a new request *A–E* arrives with a bandwidth requirement of 1 slot, the routing algorithm first calculates all possible routes, resulting in the five shortest paths as shown in Fig. 2(b). There are six paths from A to E in total, but path *ADBCFE* is omitted since we consider only k ($k=5$) shortest paths for each source–destination pair. All arrows in Fig. 2(b) indicate the different possible routes and spectral positions to provision the requested circuit *A–E*. Note that, when a spectral block with more than one slot is available for this one-slot request, the first-fit rule applies and only the slot assignment in the bottom

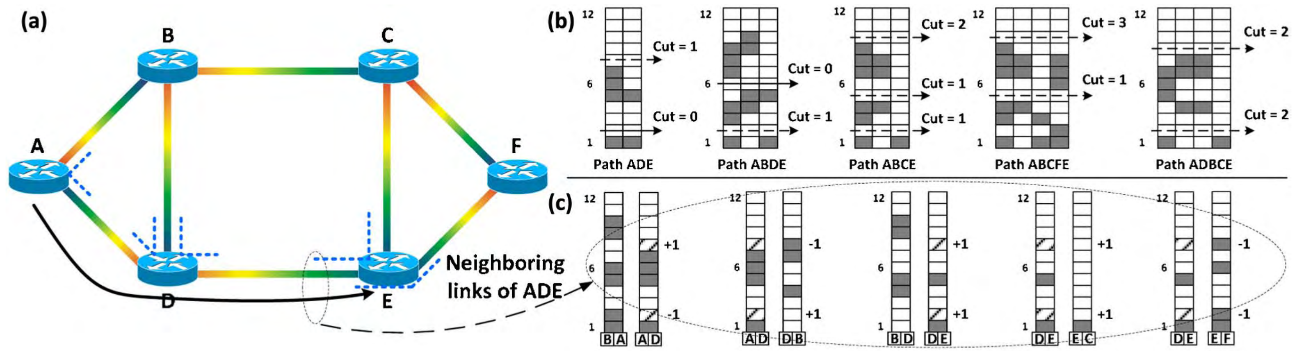

Fig. 2. (a) Example FISH network and the spectral assignment status on the links, (b) number of cuts to all the candidate solutions to connection request *A*–*E*, and (c) misalignment increase for the choice of path *ADE* with slot 8 or slot 2.

(the lowest spectrum frequency) of the block is taken. In Fig. 2(b), one "cut" indicates that the candidate RSA solution will break the contiguousness of a spectral block on one of the links on the current path. The cuts are considered to be the costs of the candidate solutions, since more cuts create more fragments on the candidate links of the routes. For example, the provisioning of the request on path *ABCE* with slot 10 will cut two spectrum blocks on links *BC* and *CE*, namely, the contiguous spectral slots 9–12 on link *BC* and spectral slots 2–12 on link *CE*. Likewise, the other provisioning choices cut different numbers of spectrum blocks on their corresponding routes. The spectrum blocks become more fragmented as they lose continuousness in the spectral domain. In the example in Fig. 2(b), the provisioning choices with solid arrows on the path *ADE* and *ABDE* both give zero cuts; therefore, they are the most preferred solutions in terms of spectral fragmentation awareness.

On the other hand, the provisioning of a request can also increase the misalignment of the available spectral blocks between the candidate links and their neighboring links. The optimized spectrum assignments are keeping the unused spectrum on neighboring links aligned for future requests. For example, the candidate provisioned on slot 8 (the top slashed blocks) will change the alignment of the neighboring links as shown in Fig. 2(c). The misalignment for the link pair *BA* and *AD* will increase by one, since the provisioning on link *AD* on slot 8 reduces the commonly available spectrum by one slot. Likewise, all the misalignment changes of neighboring link pairs along the candidate path *ADE* can be calculated. Note that, if the provisioning fills up the originally misaligned spectrum, as shown for link pair *DE* and *EF* in Fig. 2(c), the misalignment decreases by one. If the requested bandwidth is more than one slot, the "misalignment increase" is counted accumulatively over all slots. The increased misalignment in a network is considered as an additional cost for future lightpath provisioning and spectrum defragmentation. Therefore, among all candidate solutions, the algorithm should minimize the misalignment cost as well.

Overall, the cuts and misalignment increase costs are the two proposed metrics in the lightpath provisioning process. However, the minimal-cut solutions may conflict with the minimal-misalignment-increase solutions. Therefore, the fragmentation-aware RSA algorithms should take into account both costs jointly.

III. Fragmentation-Aware RSA Algorithms

The proposed fragmentation-aware RSA algorithm takes into account both the spectral fragmentation problem on each link and the spatial fragmentation problem between the candidate links and their neighboring links. Note that we refer to the spatial fragmentation as the problem of misaligned spectrum slots between neighboring links. As Table I indicates, Algorithm 1 simply gives higher priority to the cost cuts and calculates the spectral fragmentation first. It tries to minimize the number of cuts on the candidate routes and spectrum slots in the first loop of optimization. If there is more than one RSA solution that achieves the identical minimum number of cuts, then the algorithm starts the second loop of optimization, which calculates the misalignment increase between the candidate links and their neighboring links. In the end, the algorithm provides the optimized RSA solution with both minimum cuts and minimum increase in misalignment. The shortest-path first-fit rule kicks in if more than one RSA solution is found after the second loop of optimization.

The time complexity for each step of Algorithm 1 is analyzed in detail as shown in Table I. Here k is the variable that indicates the number of shortest paths calculated at the first step of the algorithm, n is the number of nodes in the network, d is the maximum degree of one node, and C is the capacity in number of slots on a single link. In a connected graph, the maximum number of hops that a path can go through without loops is $n-1$. Therefore, the counting of the parameter cuts on all of the candidate routes and spectrum assignments takes $O(knC)$ time. The search for all of the link pairs between the candidate links and their neighboring links requires a time complexity of $O((d-1)n) = O(dn)$, since there can be at most $d-1$ neighbors for a single node on a path of at most n nodes, where d is the maximum node degree. Assume that we store the spectrum utilization for each link in a linear binary array where "one" represents a free slot and "zero" represents a used slot. The calculation of misalignment increase for each link pair can run in $O(\log C)$ time, since it

TABLE I
FRAGMENTATION-AWARE RSA ALGORITHMS

Algorithm 1: Fragmentation-Aware RSA (FA)
1. Calculate k shortest routes from S to D and add them to the set P;
2. For each candidate route r in P (*loop* #1);
   For each candidate assignment in r (*loop* #2);
     Count the number of cuts as F_c on the links; $O(n)$
   End of loop #2 $O(nC)$
   End of loop #1 $O(knC)$
3. Choose the route and spectrum assignment(s) with minimum F_c; $O(kC)$
4. If there is only one RSA solution with the minimum F_c, return the solution and program ends; otherwise, go to step 5;
5. For every candidate RSA solution with the minimum F_c (*loop* #3)
   Generate link pairs between the candidate links and their neighboring links; $O((d-1)n) = O(dn)$
   For every generated link pair (*loop* #4)
   Calculate the misalignment change; $O(\log C)$
   End of loop #4; $O(dn \log C)$
   Sum up the misalignment change for all link pairs as F_m,
   End of loop #3; $O(kCdn \log C)$
6. Choose the RSA solution with the min F_m; $O(kC)$
7. If there is only one RSA solution with the minimum F_m, return the solution and program ends; otherwise, choose the RSA solution with shortest route and first-fit spectrum assignment, program ends; $O(knC) + O(kCdn \log C) = O(kCdn \log C)$.

Algorithm 2: Fragmentation-Aware RSA with congestion avoidance (FA-CA)
1. Calculate k shortest routes from S to D and add them to the set P;
2. For every candidate route r in P (*loop* #1);
   For every candidate assignment in r (*loop* #2);
     Count the number of cuts as F_c on the links; $O(n)$
     Generate link pairs between the candidate links and their neighboring links; $O(dn)$
     For every generated link pair (*loop* #3);
     Calculate the alignment change; $O(\log C)$
     End of loop #3
     Sum up the alignment change for all link pairs as $F_m O(dn \log C)$
   End of loop #2
   Calculate the current capacity C on the candidate route (the # of commonly available slots on all links) $O(n) + O(\log C)$
   Calculate the parameter F_{cmt} as in Eq. (1); $O(dn \log C)$
   End of loop #1 $O(kCdn \log C)$
3. Choose the RSA solution with the min F_{cmt}; $O(kC)$
4. If there is only one RSA solution with the minimum F_{cmt}, return the solution and program ends; otherwise, choose the RSA solution with shortest route and first-fit spectrum assignment, program ends; $O(kdnC \log C)$

first calculates the XOR value spectrum utilization arrays for the link pair (constant time) before and after the lightpath provisioning and then compares the change in the Hamming weight of the two strings. The calculation of the Hamming weight of a binary string takes $O(\log C)$ time, assuming a tree-based population count algorithm [16]. Therefore, the calculation of the misalignment increase for a candidate can run in $O(dn \log C)$ time. The overall time complexity of the proposed fragmentation-aware algorithm is $O(kdnC \log C)$.

In addition, we note that, when the network traffic load is low, introduction of the fragmentation awareness in the RSA algorithm significantly reduced the BP. However, when the network is heavily loaded, congestion on some of the links becomes the major reason for blocking. Therefore, we also propose Algorithm 2, i.e., the fragmentation-aware RSA with congestion avoidance, to address this issue. In this algorithm, we define a new parameter F_{cmt} (the fragmentation ratio which considers cuts, misalignments, and traffic) as follows:

$$F_{cmt} = F_c + F_m/(S \times N) + H \times S/C, \qquad (1)$$

where F_c and F_m represent the number of cuts and the misalignment increases mentioned in Table I, respectively; S is the number of slots requested by one connection, N is the number of neighbor links for the candidate path, H is the number of hops for the candidate path, and C is the residual capacity on the candidate path, which can range from 0 to 400 (assuming 400 spectral slots in a fiber). The second term in polynomial (1) is the normalized misalignment factor, which ranges over $[-1, 1]$. Without normalization, the misalignment factor F_m is in the range of $[-S * N, S * N]$, while the cut factor is in the range of $[0, H]$. Since for each hop there is usually more than one neighboring link in both NSFNET and USBN, the value of $S * N$ is usually much larger than H. We normalize the misalignment factor in order to put more weight on the cut factor in the overall generation of F_{cmt}, since a higher priority is also given to cuts in Algorithm 1. The third term in polynomial (1) is the load balancing factor. It is small (<1) when the traffic load is low and C is large. However, this third term becomes the dominant factor ($\gg 1$) in the polynomial when the path is congested. The algorithm calculates F_{cmt} when a candidate route and spectrum assignment solution is chosen. Among all of the solutions, the minimum F_{cmt} indicates the least fragmentation solution when the traffic load is low and indicates the least congested solution when the traffic load is high.

The time complexity of Algorithm 2 is also analyzed in Table I. Note that the calculation of F_{cmt} for one candidate RSA solution takes a constant time after each term in the polynomial is determined. In the worst case, there can be kC candidate RSA solutions in the network; therefore, the overall time complexity of proposed Algorithm 2 is $O(kdnC \log C)$ as well.

We have conducted simulations on sample network topologies to evaluate the proposed algorithms and compare them with the commonly used benchmark RSA algorithms, namely, the shortest path routing and first-fit spectrum assignment (SP-FF) algorithm and the K-shortest path routing and first-fit spectrum assignment (KSP-FF) algorithm. Dynamic connection arrival and departure events are simulated on a 14-node NSFNET network and on a 24-node USBN network, respectively. Each spectral slot is set to be 12.5 GHz, and each fiber link has 400 slots. In the simulation, each source–destination pair is generating connection requests randomly according to a Poisson process. The offered load is controlled by changing the average of the Poisson process in the range over [0.8, 10] arrivals per time unit. The holding time of each connection follows a negative exponential distribution averaging 5 time units. The connection bandwidth is randomly distributed in the range of $L = [1 \text{ slot}, 10 \text{ slot}]$.

Figure 3(a) compares the BP of the different RSA provisioning algorithms in the 14-node NSFNET. The proposed fragmentation-aware RSA algorithm (FA) outperforms the SP-FF and KSP-FF algorithms, and the fragmentation-aware RSA with congestion avoidance algorithm (FA-CA) slightly outperforms FA. Note that the BP reduction comes mainly from the use of the k-shortest path routing, where $k = 5$ in all of the simulation assumptions. However, compared to the KSP-FF, the proposed two algorithms can still achieve remarkable BP improvements. Specifically, in the NSFNET, the FA algorithm can achieve a BP improvement of 99.62%, 26.16%, 8.14%, and 4.43% at traffic loads of 180, 360, 540, and 720 erlangs, respectively. However, the FA-CA algorithm can achieve BP improvements of 99.62%, 32.96%, 11.02%, and 6.45% at traffic loads of 180, 360, 540, and 720 erlangs, respectively. Here the 99.62% BP improvement means that the BP of the FA/FA-CA algorithm is 99.62% lower than the BP of the KSP-FF algorithm. Note that at very low traffic loads (e.g., 120 erlangs), the proposed algorithms are able to reduce the BP from, for example 1.06×10^{-4} to zero, which means a 100% reduction. The relative BP improvement drops as the traffic load increases, simply because the network becomes more congested, and hence there is little room for fragmentation awareness to improve spectral efficiency (e.g., fewer options for available paths or spectrum slots). The introduction of the congestion avoidance scheme in the FA-CA algorithm reduces the BPs by an additional 2%–3% on average compared with the FA algorithm. The simulation results for the 28-node USBN network shown in Fig. 3(b) are similar to those shown in Fig. 3(a). The FA and FA-CA curves are closer to the KSP-FF curve in USBN than in NSFNET because there are more alternative paths in USBN, which gives more power to the KSP-FF algorithm in terms of reducing BP. However, even in USBN, the FA-CA algorithm can still achieve up to 20.64% in BP improvement (at the load of 180 erlangs) compared to the KSP-FF algorithm. We can draw a hypothesis that the proposed FA/FA-CA algorithms perform more significantly in a sparse graph than in a dense graph, but more effort is needed to further prove such a hypothesis, and such activities are ongoing. Please note that the proposed algorithms are very simple (only the polynomial time complexity is added to the k-shortest path routing algorithm), and thus it is worthwhile to introduce the proposed scheme to alleviate the fragmentation-caused blocking in the lightpath provisioning process. The fragmentation-aware RSAs are not intended to replace the defragmentation schemes, as the defragmentation is a reactive approach to eliminate fragments after the spectrum resources are fragmented due to, for instance, the dynamic nature of the traffic.

Furthermore, in the dynamic network scenario, the event of a lightpath release can also trigger the increase (or decrease) in terms of spectral and special fragmentation, and such an increase or decrease may in turn affect the BP of the next lightpath provision. However, our proposed algorithms do not track or affect the fragmentation changes in the event of a lightpath release. Such investigation is included in the second phase of our fragmentation-aware RSA studies.

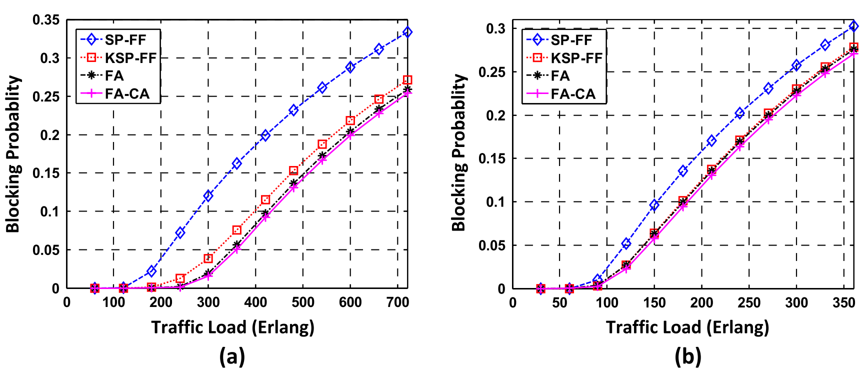

Fig. 3. Blocking probability comparison of different algorithms in (a) the 14-node NSFNET network and (b) the 28-node USBN network.

IV. Conclusion

In this paper, we have investigated the spectrum fragmentation problem in EON in both the spectral and the spatial dimensions and have proposed two fragmentation-aware RSA algorithms to proactively prevent fragmentation when routing and assigning the spectrum to the incoming lightpath requests. The detailed time complexity analysis of the proposed algorithm is presented in the paper. Both algorithms can run in $O(kdnC \log C)$ time after the k-shortest path routing process. Simulation results show that the proposed RSA algorithms reduce the BP in the two representative US core network topologies. In NSFnet, compared with the benchmark KSP-FF algorithm, the BP reduction of the FA and FA-CA algorithm ranges from 99.62% to 4.43%, and from 99.62% to 6.45%, respectively, according to the traffic load. It is worthwhile to use such schemes to introduce fragmentation awareness given the simplicity of the proposed algorithms.

Acknowledgments

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