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Fragmentation-Aware Routing Algorithms for Multicast Problem on Elastic Optical Networks

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Elastic Optical Networks (EONs) are considered as very promising architectures for future optical transport networks, since they efficiently use the spectrum resources and provide high bandwidth scalability and granularity. In this paper, the multicast routing problem in EON is considered. A fragmentation-aware multicast routing algorithm, named as Weighted Dynamic Fragmentation-aware Multicast Routing Algorithm (W-DFMRA), is proposed to solve this problem. Simulations show that the fragmentation and blocking ratio of the proposed algorithm can achieve good results.

Keywords: elastic optical network, multicast, fragmentation-aware, algorithm, multicast-capable (MC)

1. INTRODUCTION

Recently, the Internet traffic demand is rising up by approximately 40% every year, corresponding to the doubling of the demand every two years [1]. Furthermore, it is very likely that this trend will continue due to the massively increasing number and use of Internet services such as Video on Demand (VoD), high definition Internet Protocol (IP) TV, cloud computing, and grid applications requiring a high amount of data rate.

Elastic Optical Networks (EONs) 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 [2, 3]. Besides, more efficient spectrum allocation is achieved in these networks due to flexible grid and elastic line rates providing finer granularity. Moreover, these differences become more substantial when the traffic demand varies in a wide range [2, 3]. EONs provide a super-channel connectivity for accommodating ultra-high capacity demands and a subwavelength granularity for low-rate transmissions.

Due to the *spectrum continuity constraint* [2, 3], there is a tight coupling between spectrum allocation and routing of a demand. Consequently, *Routing and Spectrum Assignment* (RSA) [2, 3] 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 FSs [2]. For a given connection request, the goal of the RSA problem is to find a lightpath and allocate the required number of FSs to route the request. Because the connections are added and removed dynamically, it will cause

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spectrum fragmentation [2] and result in spectrum inefficient. So how to reduce bandwidth fragmentation effectively becomes an important issue in EONs.

In this paper, the fragmentation-aware idea [4] is applied to solve the multicast routing problem in EONs. According the survey by the authors, there is no article takes the fragmentation-aware idea for multicast routing into consideration in the literature. For a given EON and a multicast request, the goal is to find a multicast tree and assign FSs to the multicast tree to route the multicast request. A fragmentation-aware multicast routing algorithm is proposed to solve the multicast routing problem and the algorithm is named as the *Weighted Dynamic Fragmentation-aware Multicast Routing Algorithm* (W-DFMRA). In the proposed algorithm, three metrics are considered and the performance of each metric is examined through simulations. We focused on the fragmentation-aware routing method, so that the blocking ratio (BR) of the multicast requests can be reduced.

The rest of the article is organized as follows. First in Section 2 the related work is given. In Section 3, the definition and assumptions of the problem are given. In Section 4, the proposed algorithm is described. Then, in Section 5, the performance of the proposed methods is examined. The conclusions are drawn in Section 6.

2. RELATED WORKS

In this section, the related works of the studied problem will be described.

2.1 Fragmentation in EONs

The fragmentation problem in EON evolves in two dimensions, *i.e.*, in the *spectral* and *spatial domains* [4-6]. There are a few previous investigations that addressed the problem of fragmentation in EON [7-9] for unicast routing problems. *Defragmentation* schemes, which reactively reconfigure the spectrum after it is fragmented, have attracted a lot of attention [10-13]. However, it is always beneficial to pre-defragment the spectrum when a new connection is set up; for example, the RSA process takes the factor of spectrum fragmentation into account and selects the route and spectrum assignments to prevent such a problem [14].

In [14], authors considered fragmentation while performing RSA; however, they dealt only with the fragmentation between the candidate links and their neighboring links. For each candidate fiber link and its neighbors, the evaluation function [14] had to run before and after each potential spectrum assignment (the total number of candidates was large). Also, the computational complexity of the algorithms was high.

2.2 Fragmentation-aware RSA in EONs

In [4], the authors extended OpenFlow-based control plane for intelligently routing connection requests to avoid spectrum fragmentation. Two fragmentation-aware RSA algorithms are proposed, which are referred to as the *Minimum Path Cut* (MPC) algorithm and the *Minimum Path Cut with Network Resource Optimization* (MPC-NRO) algorithm. The MPC algorithm calculates all the feasible paths and then selects a path with the minimum “MPC” value to route the request, which can minimize the newly introduced fragmentation for an incoming connection. The overall feasibility and efficiency of the proposed scenario is validated by using both numerical simulation and experimental demonstration.

The *cuts* and *misalignment increase costs* are the two proposed metrics in the light-path provisioning process. The "cut" is a nonnegative integer accounting for the number of consecutive spectrum that a new connection will break [4]. Consider the example shown in Fig. 1, an incoming connection request from node v_1 to node v_4 for one slot bandwidth can be assigned to slot 4, 5 or 6 on the path. The provisioning with slot 4 will break the connective spectrum blocks on link 2 and link 3, so the cut is 2 for the assignment. Clearly, for a given connection, the cut value is a straightforward metric to evaluate its newly introduced spectrum fragmentation along a path [4]. However, the minimal-cut solutions may conflict with the minimal misalignment increase solutions [4]. Therefore, the fragmentation-aware RSA algorithms should take into account both metrics jointly.

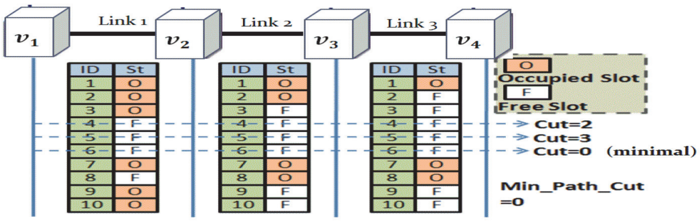


Fig. 1. Example of cut (modified from Fig. 1 in [4]).

The authors in [5] proposed joint RSA algorithms to alleviate the spectral fragmentation in the light-path provisioning process. In [5] authors found that the depicted spectrum assignment not only fills up the fragmented slot on the candidate route, but also fixes the misalignment problem between the candidate link and its neighboring links. The possible negative effect of this RSA is that it may fragment the existing continuous big spectrum block on links (breaking the continuance 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.

2.3 Multicast in EONs

Recently, based on the assumption that all optical switches are *Multicast-Capable* (MC), Wang *et al.* in [15] proposed two RSA algorithms for all-optical multicast over EONs, by leveraging the Shortest-Path Tree (SPT) and Minimum Spanning Tree (MST) based multicast-routing algorithms. The First-Fit (FF) approach was used to allocate frequency-slots. In [16], Ziyan *et al.* considered distance-adaptive frequency-slot allocation on EONs and Modulation-Enabled node Multicast Routing and Spectrum Assignment (ME-MRSA) problem, three algorithms were proposed to solve the problem.

In [17], Gong *et al.* considered the static and dynamic multicast routing problem in

EONs with multicast-capable nodes, two Integer Linear Programming (ILP) models (includes *joint ILP* and *separate ILP*) were proposed. Joint ILP considered all multicasts and optimize together, but separate ILP optimized one multicast request alone. In addition, they considered the inference from modulation-level and distance in the RMSA (Routing, Modulation-level, and Spectrum Assignment) subproblem. In order to reduce the complexity of calculating, an *Adaptive Genetic Algorithm* (AGA) was proposed to solve the problem. The dynamic multicast routing problem was also considered in [17]. The simulation results found that the genetic algorithm has shorter processing time than ILP. The blocking probability of the genetic algorithm is lower than that of the SPT and MST methods.

Several studies [18, 19] investigated *Overlay Multicast* (OL-M) in EONs built with nodes without MC capabilities. In [18], authors studied overlay multicast in *Multicast Incapable* (MI) EONs, and proposed a scheme that relies on the spectrum flexible member-only relay and denoted as OL-M-SFMOR. Simulation results indicated that OL-M-SFMOR achieves significant improvements in the spectrum-efficiency of multicast in EONs, when compared with other multicast schemes. In [19], Liu *et al.* incorporated a *layered graph approach* to design integrated *Multicast-Capable Routing and Spectrum Assignment* (MC-RSA) algorithm for achieving efficient all-optical multicast in EONs. With these procedures, the RSA for each multicast request can be done in an integrated way. Moreover, the layered graph can be used to check whether the selected multicast tree can be allocated on the selected starting FS.

3. PROBLEM DEFINITION

In this section, the assumptions, constraints, notations and the definition of the studied problem are given.

3.1 Assumptions

The assumptions of the multicast routing problem in EONs are given as follows.

- For each link in the physical network, there is a fiber connecting the end-nodes, and signals can be transmitted bidirectionally.
- All nodes in the network are equipped with MC capabilities, but without frequency-converting capabilities.
- For simplicity, the numbers of frequency slots provided by links are all equal. Each link has a limited number of FSs.
- The destinations of each multicast request are fixed and known, it is not allowed to add or remove destinations during the transmission period.

3.2 Constraints

In EONs, several constraints should be satisfied, these constraints are listed as follows.

- *Spectrum continuity*: This constraint requires that, for a given lightpath, the same block of frequency-slots of every link along the light-tree is allocated.

- *Subcarrier consecutiveness*: Due to the very nature of O-OFDM, sub-carriers of the same data stream must be consecutive along the frequency domain. Hence, all FSs assigned in a link for a given multicast request should be adjacent in the spectrum.
- *Non-overlapping spectrum assignment*: Allocated frequency slots for lightpaths (or light-trees) must be separated by guard bands in order to prevent interfering, *i.e.*, at least one FS must be assigned as a guard band between the set of FSs of every light-trees. Likewise, this constraint also implies that one FS can be employed by only a single lighttree (or lightpath) at a time.

3.3 Notations

- $G(V, E)$: The physical topology of the network, where $V=\{v_1, v_2, \ldots, v_n\}$ is the set of nodes ($|V|=n$) and $E=\{e_1, e_2, \ldots, e_m\}$ is the set of links ($|E|=m$).
- W: The number of frequency slots provided by each fiber.
- $M=(s, D, FS_M)$: The multicast request, where $s\in V$ is the source node, $D=\{d_1, d_2, \ldots, d_{|D|}\}\subseteq V$ is the set of destinations, $|D|(<|V|)$ is the size of multicast request M, and FS_M is the bandwidth requirement of the multicast request M and is represented by the number of required FSs.
- $MT=(V_T, E_T)$: The light-tree for carrying the traffic of the multicast request M, where $V_T \subseteq V$ is the set of tree nodes and $E_T \subseteq E$ is the set of edges on the light-tree.
- $B_l(j)$: The state of the jth frequency slot of the link e_l, $e_l\in E$. $B_l(j)=1$ represents the jth FS of the link e_l is occupied; $B_l(j)=0$, otherwise.

3.4 Performance Criteria

- *Blocking Ratio* (BR): BR is the ratio of the number of multicast requests blocked by the network to the number of all multicast requests arrived at the network. Smaller BR means that the network can provide services for more multicast requests simultaneously.
- *Fragmentation* (FR): The *fragmentation rate* of the link e_l, denoted fr_l, is defined as following equation:

$$fr_l = \frac{Q(e_l)}{W - \sum_{j=1}^{W} B_l(j)}, \tag{1}$$

where $Q(e_l)$ is the maximal continuous block of free frequency-slots on the link $e_l\in E$, $0\leq Q(e_l) \leq W$ and the total free frequency-slots on the link e_l can be computed by $W - \sum_{j=1}^{W}$. Rate fr_l is a ration within [0, 1], greater fr_l, means more contiguous free frequency-slots can be used on link e_l. And let FR_l be the indicator of the link e_l, FR_l is set to 1 if $fr_l \geq 0.5$, it means that free frequency-slots on link e_l are not fragmented. The formula is defined as follows:

$$FR_l = \begin{cases} 1, & \text{if } fr_l \geq 0.5 \\ 0, & \text{otherwise} \end{cases}, \tag{2}$$

And let fragmentation $FR = \sum_{\forall e_l \in E} FR_l$ be the summation of the indicators for all links in E. Greater FR means that the free frequency slots of the links in the network are less fragmented.

In this paper, given an EON network $G(V, E)$ and a multicast request $M=(s, D, FS_M)$, the goal is to find a multicast tree and allocate the required frequency slots to route the multicast request. The *Weighted Dynamic Fragmentation-aware Multicast Routing Algorithm* (W-DFMRA) is proposed to solve the problem. The details of the proposed algorithm are described in the following section.

4. W-DFMRA

The fragmentation-aware RSA algorithm takes into account both the spectral fragmentation on each link and the spatial fragmentation between the candidate links and their neighboring links. To extend this concept to design fragmentation-aware multicast routing algorithm, all links and their neighboring links of the candidate trees should be considered. In this section, the W-DFMRA is described. First, three different metrics are introduced in Section 4.1. Then, the weighted scheme is discussed in Section 4.2. Final, the details of W-DFMRA are described in Section 4.3.

4.1 Metrics

Three metrics are defined here for considering in fragmentation-aware multicast routing in EON. The first two metrics are extended from fragmentation-aware RSA problem (defined in [5]) in EON. The third metric is the average load of the candidate tree on the network. These metrics are described as follows.

- *Cut*: denoted as FC_{ij}, for the candidate tree T_i, the cut of the tree T_i on the $j \sim j+FS_M+1$ FSs is defined by following equation:

$$FC_{ij} = \sum_{e_l \in T_i} cut_{ij}^{l}, \tag{3}$$

where $cut^l_{ij} \in \{0,1\}$ represents the cut status of the link e_l for allocating the multicast tree T_i on the $j \sim j+FS_M+1$ FSs. If the $j \sim j+FS_M+1$ FSs are allocated for the link e_l of multicast tree T_i and cause a cut, then cut^l_{ij} is set to 1; otherwise $cut^l_{ij}=0$. FC_{ij} is the total number of cuts by allocating multicast tree T_i to the $j \sim j+FS_M+1$ FSs. The value of FC_{ij} is within the interval $[0, |T_i|]$, where $|T_i|$ is the number of links of the candidate tree T_i.

- *Misalignment*: denoted as FM_{ij}, for the candidate tree T_i on the $j \sim j+FS_M+1$ FSs, is defined by following equation:

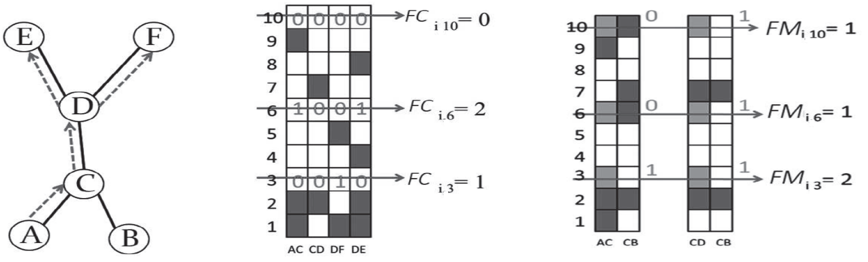
$$FM_{ij} = \sum_{\forall e_l \in T_i} \sum_{\forall e'_l \in N_{e_l}} \sum_{\forall j' \in [j, j+FS_M-1]} A_{e_l e'_l j'}, \tag{4}$$

where N_{e_l} is the set of links which are adjoined to the link $e_l \in T_i$ but not in T_i. $A_{e_l e'_l j} \in \{0, 1\}$ is the misalignment for link e_l in T_i and the neighboring link e'_l in N_{e_l} for allocating on the jth frequency-slot. If there is a misalignment, then $A_{e_l e'_l j} = 1$; otherwise, $A_{e_l e'_l j} = 0$. The value of FM_{ij} is within the interval $[0, (\max_{e_l \in T_i} = |N_{e_l}|) \times |T_i| \times FS_M] \subseteq [0, (n-1) \times |T_i| \times FS_M]$, where $|N_{e_l}|$ is the number of links in N_{e_l}.

- Average load of the tree: denoted as $L(T_i)$, for the candidate tree T_i, defined as the average load of links for the tree T_i on current EON and showed in the following equation:

$$L(T_i)=\frac{\sum_{\forall e_l \in T_i} \sum_{j=1}^{W} B_l(j)}{|T_i|}. \tag{5}$$

The value of $L(T_i)$ is within the interval [0, W].



(a) (b) (c)

Fig. 2. (a) Graph G and multicast tree T_i for the request (A, {E, F}, 1); (b) frequency-slots of links for cut FC_{ij} (c) frequency-slots of links for misalignment FM_{ij}.

Consider the example network shown in Fig. 2 (a), 10 frequency-slots are provided with each link and the multicast request is (A, {E, F}, 1). In Fig. 2 (b), the number under the horizontal arrow indicates the possible fragmented spectrum resources in links AC, CD, DF, and DE, if the multicast tree is allocated on the specific frequency-slot. The frequency-slot marked with black indicates that it is occupied, marked with white means that it is free. The fragmentation is in the spectral dimension. The number of cuts for allocating tree T_i on all possible frequency-slots are shown in Fig. 2 (b). Three possible frequency-slots can be allocated, the cut of each possible frequency-slot (3rd, 6th, 10th) is FC_{i3}=1, FC_{i6}=2, and FC_{i10}=0, respectively. The 10th frequency-slot is the best one for the multicast tree with minimal cut.

Therefore, multicast routing algorithm should assign a new multicast tree 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 [4]. The proposed algorithm should give higher priority to the selected metrics (cut, misalignment or load), and calculates the total weighted metric. It tries to minimize the number of selected metrics on the candidate trees and spectrum slots. For the same example, if the first selected metric is “cut”, the example for computing misalignments of allocating the multicast tree T_i is shown in Fig. 2 (c). The number under the horizontal arrow indicates the possible misalignments on the specific frequency-slot, if the multicast tree is allocated on the specific frequency-slot. The misalignment of allocating tree T_i the pairs of links (AC, CB) and (CD, CB) for all possible frequency-slots are shown in Fig. 2 (c). Three possible frequency-slots can be allocated, the misalignments of each possible frequency-slots (3rd, 6th, 10th) is FM_{i3}=2, FM_{i6}=1, and FM_{i10}=1, respectively; and the 10th or 6th frequency-slot is the best one.

4.2 Weighted Parameters

In this subsection, the weighted factors of the W-DFMRA is discussed. The order and weight of evaluating those metrics described in the previous section may affect the selected multicast tree and frequency-slots. In this subsection, these metrics are integrated by using a weighted function. First, all matrices are normalized within the interval [0, 1], then three weighted factors are used to compute the weighted function F_{cmt} as follows to determine the selected multicast tree and the allocated FSs.

$$F_{cmt} = \alpha \times \frac{FC_{ij}}{|T_i|} + \beta \times \frac{FM_{ij}}{FS_M \times (n-1) \times |T_i|} + \gamma \times \frac{L(T_i)}{W}, \tag{6}$$

where α, β, and γ are weighted factors.

For the parameters α, β, and γ, two parameters setting schemes are studied in this paper.

Case 1: *priority-based scheme*: α, β, and γ are in {10000, 100, 1} but with the constraint $\alpha \neq \beta \neq \gamma$. The parameter with the greatest value means that the respective metric is the most important one and will be examined first. If the first greatest metric tie, the second greatest metric is used. If the second greatest metric tie again, the last metric is used to determine the selected multicast tree and allocated FSs. For example, if (α, β, γ) = (10000, 100, 1), the cut is the first priority, the misalignment is the second and the load is the last. There are six possible cases (10000, 100, 1), (10000, 1, 100), (1, 10000, 100), (100, 100000, 1), (1, 100, 100000) and (100, 1, 10000).

Case 2: *combination-based scheme*: the α, β, and γ are within the interval [0, 1] and the values of different parameters can be the same. For example, if (α, β, γ) = (1, 0, 0), the cut is the only metric used to determine the tree and the allocated FSs. If (α, β, γ)= (1, .5, 0), then two metrics (cut and misalignment) are used and the cut is the most important one.

4.3 Algorithm for W-DFMRA

In this subsection, the details of the W-DFMRA are described. To find a light-tree for a multicast request, the *Multicast Tree Finding Algorithm* (MTFA) is used in this article. The MTFA is modified from the well-known single-source shortest path algorithm (or Dijkstra's shortest path algorithm). In MTFA, first, for a graph with nonnegative cost and a multicast request, the Dijkstra's shortest path algorithm [20] is used to find an initial shortest path tree. Then, those nodes and links which are not used to reach the destinations are pruned from the shortest path tree to form the primary multicast tree.

To simplify the illustration for finding the multicast tree in EON, the *layered graph* [19] is used. For the network $G(V, E)$ and the given multicast request $M = (s, D, FS_M)$, the *layered graph* (*LG*) is a set of graphs LG=$\{G^j(V^j, E^j), j = 1, 2, \ldots, W-FS_M+1\}$. For the graph $G^j(V^j, E^j)$, where $V^j = V$ and

$$E^j = \left\{ e_l^j \mid B_{lj} = \sum\nolimits_{z=j}^{j+FS_M-1} B_l(z) = 0,\ e_l \in E \right\}. \tag{7}$$

On $G^j(V^j, E^j)$, edge $e^l_j \in E^j$ represents that there are free contiguous frequency slots within j~$j+FS_M+1$ on the link $e_l \in E$. If a lightpath (or light-tree) can be found on $G^j(V^j, E^j)$, it means that the lightpath (or light-tree) can be allocated on network G and the starting index of frequency-slots is j and for FS_M continuous frequency-slots.

For the multicast request $M=(s, D, FS_M)$, the *Candidate Trees Finding Algorithm* (CDFA) is performed to find the set of candidate trees $TS=\{T_1, T_2, \ldots, T_k\}$ on graph $G(V, E)$. The details of the CDFA are described in **Algorithm 1**.

Algorithm 1 : Candidate Trees Finding Algorithm (CDFA)

```
Input: $G(V, E)$, multicast request $M = (s, D, FS_M)$;
Output: a set of candidate trees;
Perform the MTFA on $G$ to find the multicast tree $TR = (V', E')$.
if ($TR$ cannot be found) then
    block the request.
else
    $TS = \emptyset$, $T_1 = TR$. Add $T_1$ to the set $TS$ and $k$=2.
    All links in $TR$ are sorted in increasing order according to the distance of the links.
    while ( $k \leq |E'|+1$) do
        The $k^{th}$ smallest link $e_k \in E'$ is selected and a new graph $G'$ is constructed by removing
        $e_k$ from the graph $G$, i.e., $G' = G \setminus e_k$.
        Perform the MTFA on graph $G'$ to find a tree $T_k$.
        if ($T_k \notin TS$) then
            Add $T_k$ to the set $TS$.
        end if
        Increase the value of $k$ by 1.
    end while
end if
return $TS$.
```

In CDFA, first, the MTFA is applied on G to find the multicast tree TR. If the multicast tree TR cannot be found, then the multicast request is blocked. After finding the multicast tree TR, edges in $e_l \in TR$ are removed one-by-one from the network G to form a new graph $G-e_l$. Then, the MTFA is performed on graph $G-e_l$ again to find a candidate tree. These trees and the tree TR form a set of candidate trees, without loss of generality, the set of multicast trees is denoted as $TS=\{T_1, T_2, \ldots, T_K\}$.

Then, candidate tree $T_i \in TS$ (i=1, 2, ..., K) is selected and examined whether it can be allocated to the network G^j, for all the possible starting indices j (j=1, 2, ...,$W-FS_M+1$) of frequency-slots. If the multicast tree $T_i \in TS$ can be allocated on layered graph G^j, then three metrics FC_{ij}, FM_{ij}, and $L(T_i)$ (cut, misalignment, and load) of each candidate tree on G at the starting index j are computed. Then the weight function F_{cmt} of each feasible tree and available FSs is computed. The tree on the selected FSs with minimal weight F_{cmt} is allocated.

If the parameter is set as (10000,100, 1), then the multicast tree with minimum cut (*i.e.*, $\min_{\forall i} \min_{\forall j} \{FC_{ij}\}$, i = 1, 2, ..., K; j=1, 2, ..., $W-FS_M+1$) is selected. If there is more than one candidate tree that achieve the identical minimum cuts, then the proposed algorithm will be selected the one with minimal misalignment as the candidate tree to allocate. If there are more than one candidate trees that achieve the identical minimum cuts and minimum misalignment, then the proposed algorithm will select the tree with minimal load. The minimal-hop first-fit rule kicks in if more than one multicast trees are found. The details of the W-DFMRA are described as in **Algorithm 2**. T_b is the set of the trees with minimal weight, F_b is the best weighted metric.

Algorithm 2 : Weighted Dynamic Fragmentation-aware Multicast Routing Algorithm (W-DFMRA)

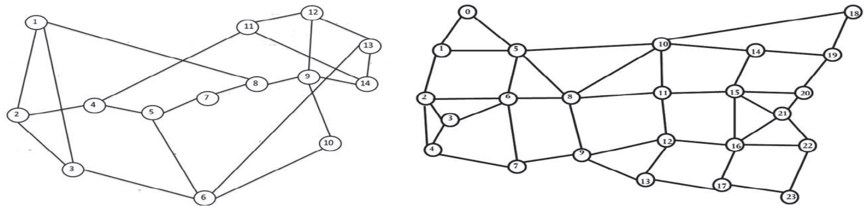
```
Input: $G(V, E)$, multicast request $M = (s, D, FS_M)$, weighted parameters $\alpha$, $\beta$, and $\gamma$;
Output: multicast tree;
Perform the CDFA to find a set $TS$ of candidate trees. Let $TS = \{T_1, T_2, ..., T_K\}$ be the set of candidate trees.
Let $i = 1$, $T_b = \emptyset$ and $F_b = -\infty$.
while $(i \leq K)$ do
    {  //for all candidate tree
    $j = 1$.
    while $(j \leq W - FS_M + 1)$ do
        {  //for all possible frequency slots
        if ($T_i$ can be allocated on $G^j(V^j, E^j)$) then
            Compute the cost $F_{cmt} = \alpha \times \frac{FC_{ij}}{|T_i|} + \beta \times \frac{FM_{ij}}{FS_M \times (n-1) \times |T_i|} + \gamma \times \frac{L(T_i)}{W}$ of the tree $T_i$ on $G^j$.
            if $(F_{cmt} < F_b)$ then
                Delete all trees in $T_b$, add $T_i$ to $T_b$, and $F_b = F_{cmt}$.
            else if $(F_{cmt} == F_b)$ then
                Add $T_i$ to $T_b$
            end if
        end if
        $j = j + 1$.
        }
    end while
    $i = i + 1$.
    }
end while
if $(F_b == -\infty)$ then
    return block the multicast request.
else if $(|T_b| == 1)$ then
    return the tree in $T_b$.
else
    Find the tree in $T_b$ with minimum hops and construct set $T_h$ to store trees with minimum hops.
    if $(|T_h| == 1)$ then
        return the tree in $T_h$.
    else
        random select a tree $T_i$ in $T_h$ and return $T_i$.
    end if
end if
```

The computational complexity of the W-DFMRA is analyzed as follows: The time for computing the multicast tree TR takes $O(m+n\log n)$ time. Then, perform CDFA to find the set TS of candidate trees takes $O(|TR| \times (m+n\log n)) = O(mn+n^2\log n)$. Two levels of while loop are used in W-DFMRA to find the multicast tree on the specific starting index, there are $O(K \times (W - FS_M + 1)) = O(KW)$ iterations. For each iteration, the candidate tree T_i is checked whether it can be allocated on the layered graph G^j, it takes $O(|T_i| \times FS_M) = O(n \times FS_M)$ time. If the candidate tree can be allocated on the selected FSs, the cut, misalignment and load are computed. The time for computing the cut, misalignment and load of the tree T_i on network G^j takes $O(|T_i|)$, $O(|T_i| \times n \times FS_M)$ and $O(|T_i| \times W)$ time, respectively. Thus, the time spent by each iteration is $O(n \times FS_M + |T_i| + |T_i| \times n \times FS_M + |T_i| \times W) = O(n^2 \times FS_M + n \times W)$. Thus, the computational complexity of the W-DFMRA is $O(KW(n^2 \times FS_M + n \times W)) = O(KWn^2FS_M + nKW^2) = O(n^3WFS_M + n^2W^2)$.

5. SIMULATION RESULTS

The NSF network (denoted as NSFNET with 14 nodes and 24 links) and US network (denoted as USNET with 24 nodes and 43 links) were used for simulations. The topologies of the NSFNET and USNET are shown in Figs. 3 (a) and (b), respectively.

For all simulations, the number of frequency-slots (*W*) of each optical fiber is set to 100. The proposed algorithms were coded by using Java programming language. All simulations were run on a notebook computer with Intel Due Core i7-4710HW 2.5GHz CPU, 16GB RAM and with Windows 10 operating system. All the multicast requests were randomly generated and all nodes in the network can be selected as source or destinations with equal probability. The number of destination nodes of each multicast request is denoted as *dn*. The number of required frequency-slots of the multicast request is randomly selected within {1, 2, ..., *FS*}.



(a) (b)

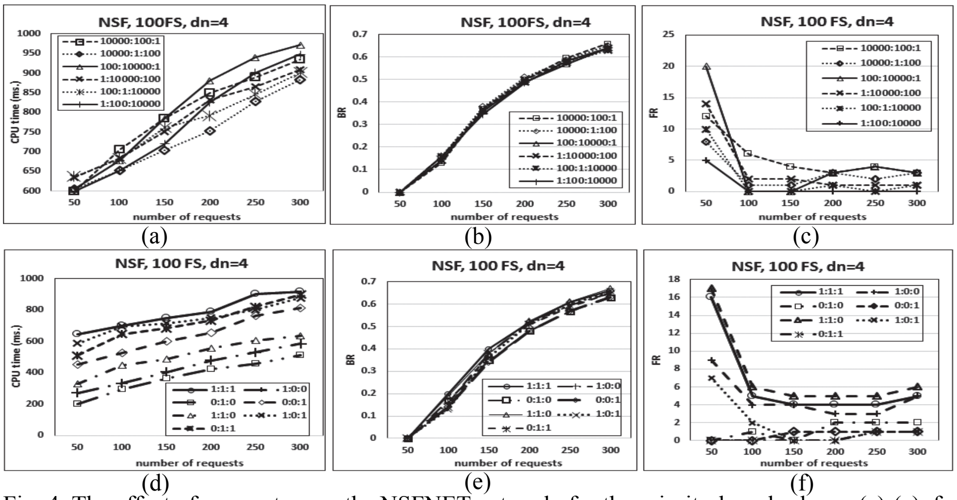
Fig. 3. Simulation networks (a) NSFNET, (b) USNET.

5.1 Parameter Setting

To know the effect of the parameters (α, β, and γ), several simulations are conducted. For these simulations, the number of destinations (*dn*) and the maximal number of required frequency-slots (FS) are set to 4, 300 multicast requests are generated randomly and used for simulations. Two parameter setting schemes are examined, and the results are shown in Figs. 4 (a)-(c) for the priority-based scheme and in Figs. 4 (d)-(f) for the combination-based scheme on the NSF network. The similar simulations on the US network are also shown in Fig. 5.

For the priority-based scheme, the results in Figs. 4 (a) and 5 (a) show that the CPU time increases as the number of multicast requests increases, for all examined cases. The case (10000, 1,100) is the fastest one and the case (100, 10000, 1) is the slowest one on the NSF network. In Fig. 5 (a), The case (100, 1,10000) is the fastest one and the case (100, 10000, 1) is the slowest one on the US network. In Figs. 4 (b) and 5 (b), the BR values of these cases are quite close (within 3%), and the case (100, 1, 10000) can get the lowest BR in these simulations. It means that to get better BR performance, if the priority-based scheme is used, the load of the candidate tree on the selected staring frequency-slot in more important than the other two metrics. In Fig. 4 (c) the method with (10000, 100, 1) can get the greatest FR for these simulations on the NSF and US networks, except for 50 multicast requests. In these simulations, the FR values in the case with 50 multicast requests are higher than other cases with more multicast requests (most of these are less than <*m*/4). These may be the reason that more free and continuous FSs are allocatable for smaller multicast requests.

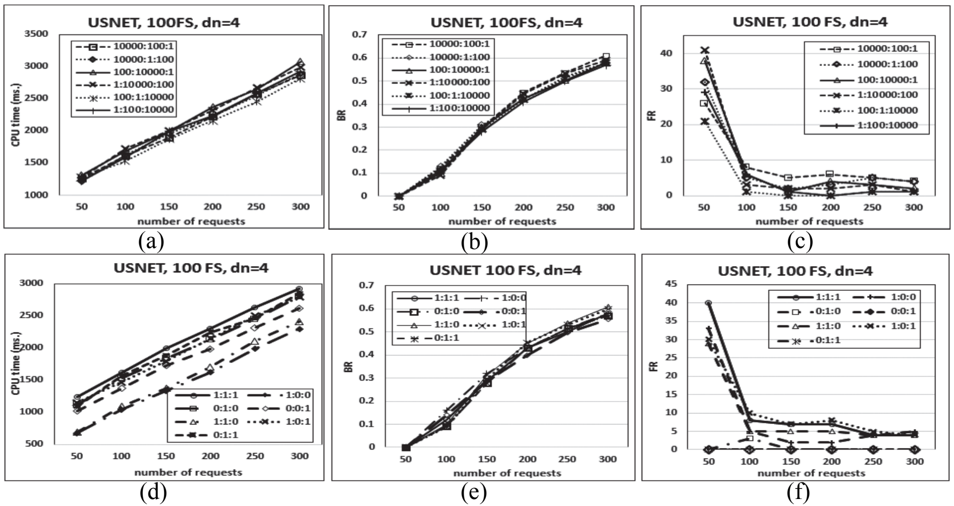
For the combination-based scheme, the results in Figs. 4 (d) and 5 (d) show that the CPU time increases as the number of multicast requests increases for all cases of parameter setting. The case (0, 1 ,0) is the fastest one and the method (1, 1, 1) is the slowest one on NSF network. Since for the parameter with zero weight, the respective metric will not computed and this can speed up the computation. In Fig. 5 (d), the case (1, 0, 0) is the fastest one and the case (1, 1, 1) is the slowest one for US network. For the larger network, the computation time for the misalignment metric is greater than that of the cut metric. In Figs. 4 (e) and 5 (e), the method with (0, 0, 1) can get the lowest BR on these simulations. Moreover, the BR of case (0, 0, 1) is less than that of the case (100, 1, 10000). In Fig. 4 (f) the case (1, 1, 0) can get the greatest FR for these simulations on the NSF network. In Fig. 5 (f), the cases (1, 0, 1) can get the greatest FR for these simulations on the US network. The second greatest FR is the case (1, 1, 1) and the third greatest FR is the case (1, 1, 0). The results show that the cut metric does affect the fragmentation ration of the EON.



(a) (b) (c)

(d) (e) (f)

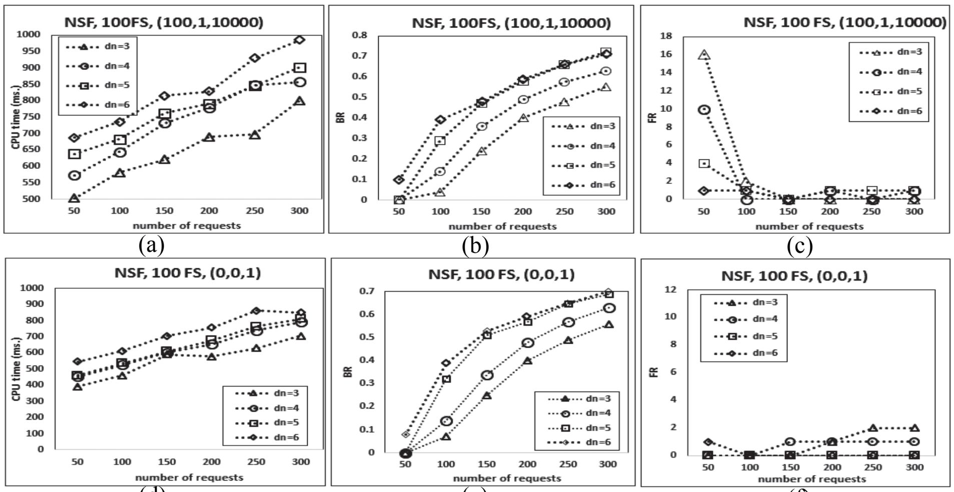
Fig. 4. The effect of parameters on the NSFNET network, for the priority-based scheme (a)-(c), for the combination-based scheme (d)-(e).



(a) (b) (c)

(d) (e) (f)

Fig. 5. The effect of parameters on the USNET network, for the priority-based scheme (a)-(c), for the combination-based scheme (d)-(e).

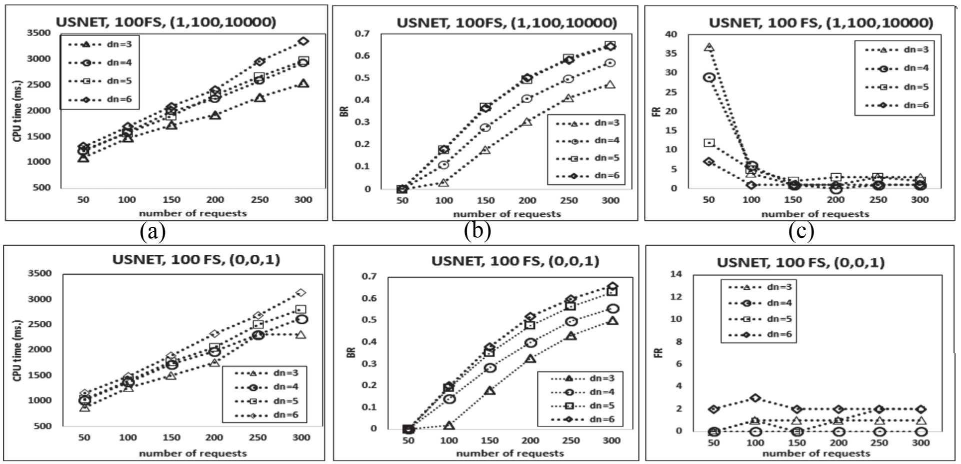


(a) (b) (c)

(d) (e) (f)

Fig. 6. Simulation results for *dn* on NSFNET: for case (100, 1, 10000) (a)-(c), for case (0, 0, 1) (d)-(f).

From the previous simulations, the metric "average load" seems to be the most important metric to reduce BR. In the following, two cases (100, 1, 10000) and (0, 0, 1) are used to examine the effect of the *dn* and *FS*. For different numbers of destinations ($dn \in \{3, 4, 5, 6\}$) and two cases (100, 1, 10000) and (0, 0, 1), the simulations on the networks NSFNET and USNET are shown in Figs. 6 and 7, respectively. The results show that as the value of *dn* increases, the CPU time increases and the BR increases on these two networks. For the results shown in Figs. 6 (c) and 7 (c), there is no significant difference on *FR* for different values of *dn* except for the case with 50 multicast requests. The *FR* value of the case (0, 0, 1) for 50 multicast requests and *dn* in {3, 4, 5} is lower than that of the case (100, 1, 10000). Since in case (100, 1, 10000), not only the load is



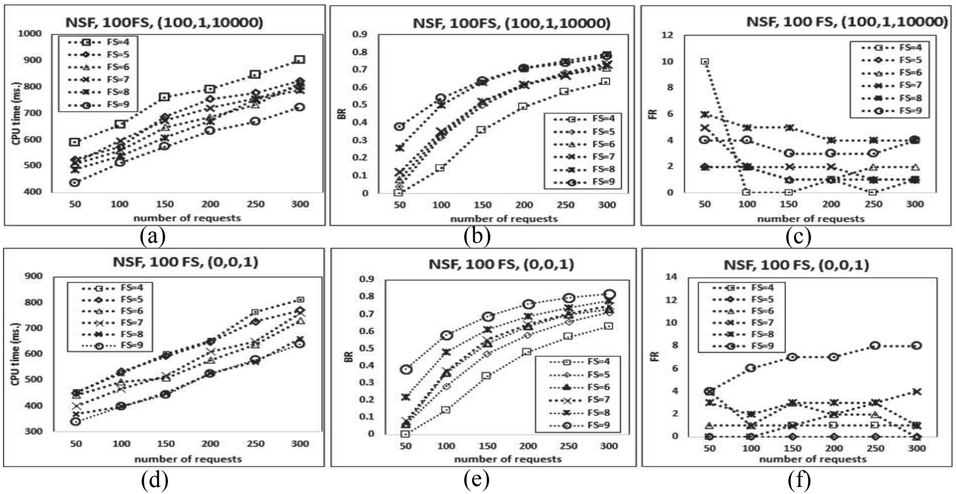
(a) (b) (c)

(d) (e) (f)

Fig. 7. Simulation results for *dn* on USNET: for the case (100, 1, 10000) (a)-(c), for the case (0, 0, 1) (d)-(f).

considered, but also the cut and misalignment metrics, the *FR* value is greater than the case (0, 0, 1).

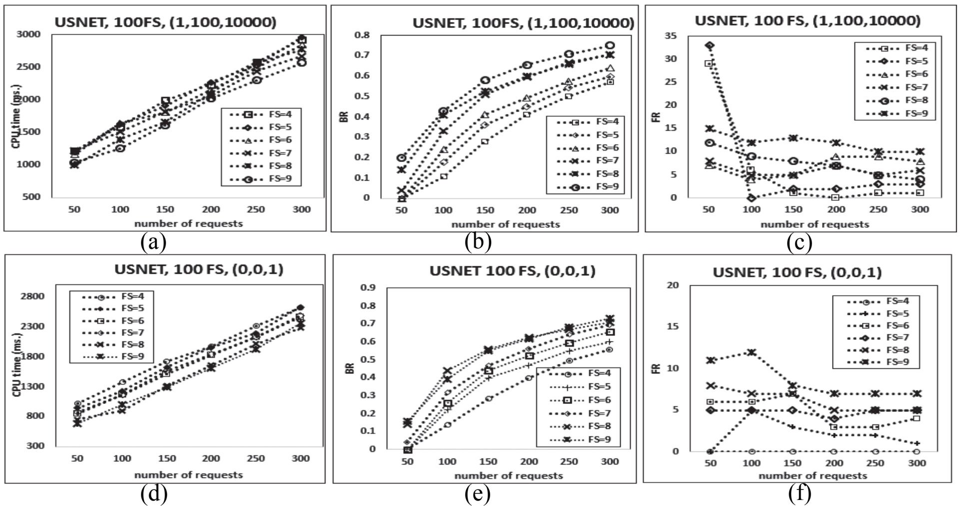
For different number of required frequency-slots ($FS \in \{4, 5, 6, 7, 8, 9\}$) and cases (100, 1, 10000) and (0, 0, 1), the simulations on the networks NSFNET and USNET are shown in Figs. 8 and 9, respectively. The results show that as the value of *FS* increases, the CPU time decreases and the BR increases on these networks. For the results shown in Figs. 8 (c) and 9 (f), for most of the cases, the *FR* increases as the value of *FS* increases, except for the case with 50 multicast requests. It means that routing requests with greater *FS* can reduce the fragmentation of frequency-slots of EON.



(a) (b) (c)

(d) (e) (f)

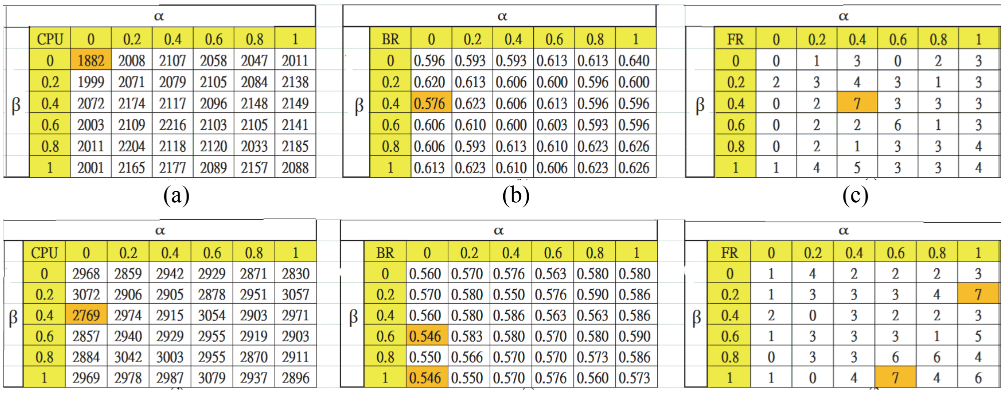
Fig. 8. Simulation results for FS on NSFNET: for the case (100, 1, 10000) (a)-(c), for the case (0, 0, 1) (d)-(f).



(a) (b) (c)

(d) (e) (f)

Fig. 9. Simulation results for FS on USNET for the case (100, 1, 10000) (a)-(c), for the case (0, 0, 1000) (d)-(f).



		α					
	CPU	0	0.2	0.4	0.6	0.8	1
β	0	1882	2008	2107	2058	2047	2011
	0.2	1999	2071	2079	2105	2084	2138
	0.4	2072	2174	2117	2096	2148	2149
	0.6	2003	2109	2216	2103	2105	2141
	0.8	2011	2204	2118	2120	2033	2185
	1	2001	2165	2177	2089	2157	2088

(a)

		α					
	BR	0	0.2	0.4	0.6	0.8	1
β	0	0.596	0.593	0.593	0.613	0.613	0.640
	0.2	0.620	0.613	0.606	0.600	0.596	0.600
	0.4	0.576	0.623	0.606	0.613	0.596	0.596
	0.6	0.606	0.610	0.600	0.603	0.593	0.596
	0.8	0.606	0.593	0.613	0.610	0.623	0.626
	1	0.613	0.623	0.610	0.606	0.623	0.626

(b)

		α					
	FR	0	0.2	0.4	0.6	0.8	1
β	0	0	1	3	0	2	3
	0.2	2	3	4	3	1	3
	0.4	0	2	7	3	3	3
	0.6	0	2	2	6	1	3
	0.8	0	2	1	3	3	4
	1	1	4	5	3	3	4

(c)

		α					
	CPU	0	0.2	0.4	0.6	0.8	1
β	0	2968	2859	2942	2929	2871	2830
	0.2	3072	2906	2905	2878	2951	3057
	0.4	2769	2974	2915	3054	2903	2971
	0.6	2857	2940	2929	2955	2919	2903
	0.8	2884	3042	3003	2955	2870	2911
	1	2969	2978	2987	3079	2937	2896

(d)

		α					
	BR	0	0.2	0.4	0.6	0.8	1
β	0	0.560	0.570	0.576	0.563	0.580	0.580
	0.2	0.570	0.580	0.550	0.576	0.590	0.586
	0.4	0.560	0.580	0.586	0.563	0.563	0.586
	0.6	0.546	0.583	0.580	0.570	0.580	0.590
	0.8	0.550	0.566	0.570	0.570	0.573	0.586
	1	0.546	0.550	0.570	0.576	0.560	0.573

(e)

		α					
	FR	0	0.2	0.4	0.6	0.8	1
β	0	1	4	2	2	2	3
	0.2	1	3	3	3	4	7
	0.4	2	0	3	2	2	3
	0.6	1	3	3	3	1	5
	0.8	0	3	3	6	6	4
	1	1	0	4	7	4	6

(f)

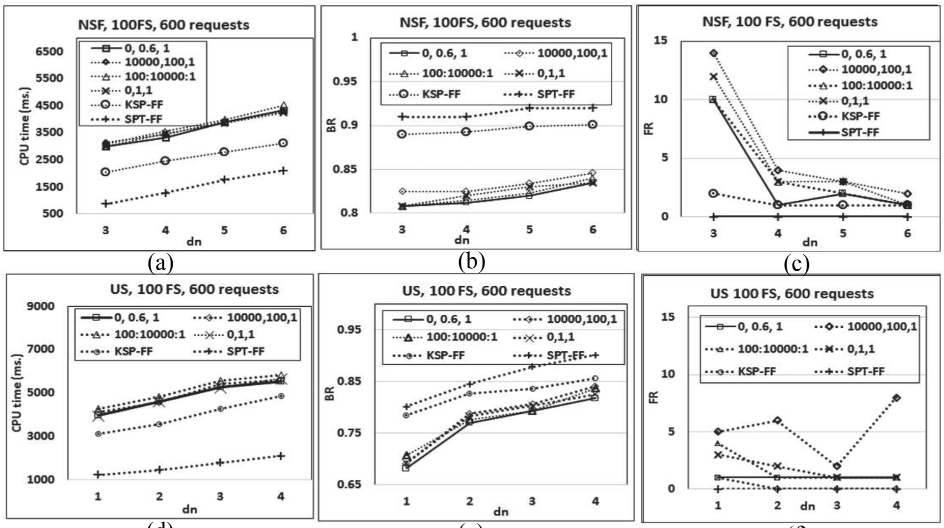
Fig. 10. Simulation for different values of (α, β) on network NSFNET, (a)-(c) and on network USNET, (d)-(f).

From the results of previous simulations, the average load of the candidate trees for the specific starting frequency-slot is the most important metric for better performance. To know the effect of the other two weighted factors (α and $\beta \in \{0, 0.2, 0.4, 0.6, 0.8, 1\}$) when γ is set to 1, several possible combinations are examined on two networks and the simulation results are shown in Fig. 10. For the NSFNET network, the case (0, 0.4, 1) can get lowest BR (0.576) and FR (0) as shown in Figs. 10 (b)-(c), respectively. For the USNET network, the cases (0, 0.6, 1) and (0, 1, 1) can get lowest BR (0.546) as shown in Fig. 10 (e) and the value of the FR is equal to 1 for these parameters. Thus, these simulations suggest that, the weighted factor (α, β, γ) is set to (0, 0.6, 1) or (0, 1, 1).

5.2 Comparisons

To evaluate the efficiency of the proposed methods, two multicast algorithms, named as *Shortest-Path-Tree First-Fit* (SPT-FF) and *K-Shortest-Path First-Fit* (KSP-FF), are also implemented for comparison. In *SPT-FF*, the shortest path tree is found as the multicast tree, then the first-fit scheme is used to determine the allocated frequency-slots. If the free FSs cannot be found, then the request is blocked. In *KSP-FF*, first, the *K* candidate multicast trees are generated and stored in the set *TS* by performing the CDFA. For each candidate tree in *TS*, the first-fit scheme is used to determine the allocated frequency-slots. If free FSs can be found for the selected candidate tree, then the resource is allocated for the multicast tree. If all candidate trees in *TS* cannot be allocated after examining all possible frequency-slots on the network, then the multicast request is blocked. In KSP-FF and SPT-FF, no fragmentation metric is considered for routing the multicast tree and/or allocating the required frequency slots. It is considered as the traditional method and used for comparison.

For 600 multicast requests, W=100, dn=4, FS=4, several possible cases of W-DFMRA are included in the comparison; they are (0, 0.6, 1), (10000, 100, 1), (100, 10000, 1) and (0, 1, 1). Together with the KSP-FF and SPT-FF methods, the simulation results are shown in Figs. 11 (a)-(c) and Figs. 11 (d)-(f) for the NSF and US networks, respectively. The results in Figs. 11 (a) and (d) show that SPT-FF and KSP-FF are faster than the W-DFMRA with all different cases. In SPT-FF, only one multicast tree is examined and the first-fit FSs are found to allocate the multicast request. This may save the time by avoiding to check all allocatable FSs. For most of the cases, the case (0, 0.6, 1) is the quickest W-DFMRA method. The results in Figs. 11 (b) and (e) show that the case (0, 0.6, 1) can get the lowest BR and the SPT-FF can get the worst BR. The results in Figs. 11 (c) and (f) show that for most of the cases, the case (0, 0.6, 1) can get better FR than that of the SPT-FF and KSP-FF.



(a) (b) (c)

(d) (e) (f)

Fig. 11. Comparisons for network NSFNET, (a)-(c) and for network USNET, (d)-(f).

6. CONCLUSIONS

In this article, the multicast routing problem in EONs has been studied. For a given EON and a multicast request, the goal is to find a multicast tree and assign frequency-slots to the request. All nodes in EON are equipped with multicast-capable capabilities. The destinations of each multicast request are fixed and known, that is, it is not allowed to add or remove destinations during the transmission period. A fragmentation-aware multicast routing algorithm, named as *Weighted Dynamic Fragmentation-aware Multicast Routing Algorithm* (W-DFMRA), has been proposed. In the W-DFMRA, three metrics (cut, misalignment, load) are designed and used to evaluate the performance of the multicast tree on the selected frequency slots. These metrics have been normalized and a weighted cost function F_{cmt} is computed and used to determine suitable spanning tree and FSs. Moreover, two parameter setting schemes were proposed and weighted factor for each metric is considered. Simulations have been conducted to evaluate the BR and FR of these weighted methods. The simulations show that the metric "average load" of the candidate tree is the most important metric and the second metric is the "misalignment". Proper selected weights can help the W-DFMRA to get lower BR. The BR of the proposed W-DFMRA is lower than that of the SPA-FF and KSP-FF algorithms.

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