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弹性光网络中选路和频谱指派的建模和高效启发式算法

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摘　要:弹性光网络可大幅度提高频谱利用率并为用户提供灵活的带宽粒度.为改进已有弹性光网络的选路与频谱分配算法,建立了描述弹性光网络中选路与频谱分配问题的整数线性规划模型,提出两种分别基于最多频隙数优先和最长路径优先与业务疏导结合的启发式算法,以进一步提高频谱利用率,设计了所提算法的重排序准则和流程.对小型 6 结点、中型 14 结点和大型 19 结点等三种不同网络拓扑进行仿真实验,结果表明,所提算法可有效提高已有算法的频谱利用率.

关键词:选路算法；启发式算法;性能评估；选路与频谱分配；业务疏导；弹性光网络；整数线性规划
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Modelling and Heuristic Algorithms for Routing and Spectrum Assignment in Elastic Optical Networks

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Abstract: Elastic optical networks could increase the sprectrum usage ratio greatly and provide users with flexible bandwidth granularity compared to the traditional wavelength division multiplexing networks. To improve the existing algorithms of routing and spectrum assignment in EONs, An integer linear programming model was set up to formulate the Routing and Spectrum Assignment problem, and two heuristic algorithms were proposed, which combine the traffic grooming with most solts first and longest path first, respectively, thereby increasing the spectrum resource utilization further. The reordering rule and procedure of the proposed algorithms were designed. The expermients under the small-size network (6-node simple network), medium-size network (14-node NSFNET) and large-size network (19-node telecommunication backbone network) show that the proposed algorithms could increase the spectrum resource utilization effectively when compared with existing algorithms.

Key words: Routing algorithms; Heuristic algorithms; Performance evaluation; Routing and spectrum assignment; Traffic grooming; Elastic optical networks; Integer linear programming
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0 Introduction

In traditional Wavelength Division Multiplexing (WDM) networks[1], the bandwidth granularity or the minimum bandwidth provided to each user request is the capacity of a fixed-size single wavelength. When the bandwidth of a connection request is less than the capacity of one wavelength, we must allocate the full bandwidth of a wavelength; oppositely, if the requested bandwidth is (a little) larger than that of a wavelength, we need to allocate several wavelengths grouped while the guard-band spectrum between the adjacent wavelengths in the group will lead to the low utilization of spectrum resources. To enable efficient resource utilization and provide flexible bandwidth granularity feasible, the concept of the spectrum-sliced elastic optical path networks (SLICEs) or Elastic Optical Networks (EONs) has been recently proposed[1-5]. EONs[1] could allocate flexibly appropriately-sized optical bandwidth for each request connection based on the use of Optical Orthogonal Frequency Division Multiplexing (OOFDM) technologies. Besides, adjacent OOFDM sub-carriers can overlap partially in the spectrum domain. The transfer bandwidth requested is carried over an optical single- or multi-hop path established by using one or multiple contiguous OOFDM sub-carriers which are referred to as Frequency-Slots (FSs)[2]. Although there is still guard-band spectrum to which is referred as Guard Frequency Slots (GFSs) between two wavebands, a lot of spectrum bandwidth could be saved without the rigid "Grids". It is the OOFDM that enables EONs feasible and such a technique could also be used in Passive Optical Networks (PONs)[6-7].

For the connection requests, the procedure[1] of the Routing and Spectrum Assignment (RSA) in EONs is very similar to that of Routing and Wavelength Assignment (RWA) in traditional optical networks. The difference is that both procedures assign the spectrum and wavelength, respectively. All FSs can be classified into three types of service-, protection- and unassigned-FS. We see that, if the spectrum converter, similar to the wavelength transformer, is not used, each lightpath must satisfy the continuity constraints of frequency-slot and spectrum, and each FS can only be allocated to a single request. There are GFSs between the adjacent optical spectrum paths.

The analysis above shows that EONs are more flexible than WDM networks in spectrum assignment, thus they not only provide the variable granularity but also reduce some GFSs for the larger bandwidth of each connection request. One of the main goals in EONs is to make the unused FSs as few as possible when RSA processing is completed, thus reducing the spectrum fragments[8] and increasing the spectrum utilization.

One of the main objectives for the RSA problem in EONs is to minimize the spectrum (i. e., the number of FSs or maximum sequence number of FSs) used to serve the connection request matrix. An algorithm of Fixed-Alternate routing and First-Fit spectrum assignment (FA-FF)[2] had the advantages of less computational capability and easy implementation. However, it resulted in low overall spectrum resources usage since it preferred selecting a shorter routing path.

Traffic grooming is a technique in which several low-speed services could be multiplexed onto one high-speed service and carried in one high-speed channel. Similarly, ZHANG Yi et al. used the traffic grooming strategy first time in EONs[9], and they aggregated multiple low-speed traffic requests and modulated onto the super-wavelength identified in Ref. [3]. Their method can further reduce the number of GFSs to some extent. However, the authors did not address the specific heuristic algorithm. Christodoulopoulos K et al. proposed two RSA algorithms[10-11] in which spectrum assignments are dependent on reordering the connection requests in decreasing order, i. e., the number of all requested FSs in the MSF (Most Slots First) algorithm, and the number of links used in shortest paths in the Longest Path First (LPF) algorithm. Both algorithms improved FA-FF to some extent, but the GFSs are required to separate the adjacent optical paths.

Therefore, our work is to study more efficient RSA algorithms with traffic grooming in EONs, which have lower requirements of computation capability compared to those algorithms using intelligence, such as Genetic Algorithm (GA) and Ant Colony Optimization (ACO). The proposed algorithms are very easy to be implemented and applied to dynamic user services.

1 ILP model

In this section, we present an Integer Linear Programming (ILP) formulation to model the optimal static RSA problem, which facilitates the implementation of the proposed algorithm, and the comparison of the simulated results with numerical results obtained by using some ILP software tools, e. g., IBM ILOG CPLEX Optimizer. We use $G(V,E)$ to define the graph of a network, where $V=\{v_i \mid i=1,2,\cdots,n\}$ denotes the set of its nodes and $E=\{l_{ij} \mid i,j\in V\}$ represents the set of directional fiber links between nodes in V.

An ordered set $F=\{f_1,f_2,f_3,\cdots,f_M\}$ of FSs is initially assigned to each link, where an integer M satisfies $M \leqslant |F|$ and $|F|$ denotes the maximum sequence number of FSs assigned to transfer all connection requests. We usually select $M = |F|$ and $f_i = i(i \leqslant M)$. Let $R = \{r_1, r_2, \cdots, r_{|R|}\}$ denotes the set of all connection requests. Each r_i is identified by a triple (s, d, T_i), where s and d are source and destination nodes, and T_i is the number of FSs requested by r_i.

Prior to discussing the model, we introduce a set of notations and variables as follows.

C_{fiber}: the capacity of each fiber;

C_{fs}: the capacity of each FS;

$f_{\text{sd}}^{r_i,\ \text{start}}$: the lowest indexed FS assigned to request r_i on path $p \in P_{r_i}$; here, the lowest indexed FS is such an idle and starting FS that has the minimum sequential number of FSs;

$f_{m,n,s,d}^{r_i,\text{start}}$: the lowest indexed FS assigned to request r_i on link $l_{mn} \in p$;

$P_{r_i} = \{p_{r_i}^1, p_{r_i}^2, \cdots, p_{r_i}^K\}$: the set of K candidate paths for request $r_i \in R$;

x_p: equals 1 if FS $f \in F$ on path $p \in P_{r_i}$ is selected to be the lowest indexed slot that is assigned to request r_i, and is 0 otherwise;

p: the path $p \in P_{r_i}$ carries the request r_i;

$NGFSs$: the number of guard-band FSs between adjacent spectrum bands of two lightpaths;

$V_{m,n,s,d}^{r_i,f_x}$: equals 1 if $f_x \in F$ on link $l_{mn} \in p$ is assigned to request r_i with source-destination pair of (s,d), and is 0 otherwise;

$B_{m,n,s,d}$: the number of FSs on link $l_{mn} \in p$ that is assigned to the request r_i;

MF_l: the number of FSs that needs to be assigned to each link $l \in E$.

We formulate RSA as an ILP optimization problem:

Minimize $|F|$.

Subject to the following constraints

$$|F| \geqslant MF_l, l \in E \tag{1}$$

$$C_{\text{fiber}} \geqslant C_{\text{fs}} \times |F| \tag{2}$$

$$\sum_{p \in P_{r_i}} x_p = 1 \tag{3}$$

$$\sum_{f_x \in F} V_{m,n,s,d}^{r_i,f_x} \big|_{s=d} = 0 \tag{4}$$

$$\sum_{r_i \in D} V_{m,n,s,d}^{r_i,f_x} \leqslant 1, \quad f_x \in F \tag{5}$$

$$f_{m,n,s,d}^{r_i,\text{start}} = f_{m',n',s,d}^{r_i,\text{start}} \quad (m,n),(m',n') \in p \tag{6}$$

$$\sum_n B_{m,n,s,d} - \sum_n B_{n,m,s,d} = \begin{cases} T_i & m = s \\ -T_i & m = d \qquad \forall\, m,n \in N \\ 0 & m \neq s,d \end{cases} \tag{7}$$

Eq. (1) makes sure that each link has enough FSs to meet the all requested demands without the blocking or no connection request is rejected. Eq. (2) denotes that the utilized bandwidth (including GFSs) could not exceed the spectrum capacity of a fiber. Eq. (3) indicates that we could select a path successfully from the set of candidate paths as the lowest indexed slot assigned to each connection request. Eq. (4) guarantees that each connection request could not be added and dropped at the same node. We make sure in Eq. (5) that one FS can only be used by a specific connection request. The FSs continuity constraint in Eq. (6) guarantees that the same FS (or spectrum) must be used along all links of each specific path. Eq. (7) is the flow conservation constraint at source-, destination- and intermediate-node of a specific path at optical layer.

2 TGMSF and TGLPF algorithms

In this section, we present the proposed Traffic Grooming MSF (TGMSF) and Traffic Grooming LPF (TGLPF) algorithms, which can be applied into large network scenarios. In these two algorithms, we sort the connection requests according to two policies used in MSF and LPF algorithms. Then, we select a path with lowest indexed slot (i. e., not the shortest path first) from the set of candidate paths, implementing the goal and making the load have a more unified distribution in the network.

In TGMSF and TGLPF algorithms, we use the traffic grooming algorithm to combine those connection requests that have some common links and the same source-destination pair, which could eliminate partially the number of GFSs and further improve the spectrum utilization. The starting node of the common link first demodulates the data services with the same source-destination pair from different lightpaths, aggregates data services and modulates such data services onto a super-FSs. While end node of the common link demodulates the data services again, switches such an aggregated data service in electronic domain, and modulates the separated data services onto different lightpaths. Note that this process will make the node implementation some complex.

In TGMSF algorithm, we sort the connection requests in decreasing order of each requested bandwidth T_i, and rearrange the connection requests in decreasing order of the number of hops in each candidate path $p_{r_i}^1$ in TGLPF.

TGMSF Algorithm Procedure

```
1) $R' = \{r'_1, r'_2, \cdots, r'_{|R|}\} <- R =$
   $\{r_1, r_2, \cdots, r_{|R|}\}$
2) for ($i = 1$; $i <= |R|$; $i++$)
3) $P_{r_i} = \{p_{r_i}^1, p_{r_i}^2, \cdots, p_{r_i}^K\}$
end for
4) for ($i = 1$; $i <= |R|$ ; $i++$)
5) for ($j = 1$; $j <= K$; $j++$)
6) Search for consecutive available FSs on each
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link along the path $p^j_{r_i}$ and return the smallest starting FS index of each link;
    7) if each starting FS index of each link on path $p^j_{r_i}$ is equal, this path's index is marked $p^j_{r_i}$; otherwise, go to step 6);
    end for
    8) $f_{\mathrm{sd}}^{r_i,\mathrm{start}}=\min\{f_i^1, f_i^2, \cdots, f_i^K\}$
    9) for (num=1; num<$i$; num++)
    10) if $r_i$ and $r_{\mathrm{num}}$ have a common link, and we could find feasible converged RSA solution, then release the NGFSs assigned for $r_{\mathrm{num}}$.
    end for
end for
```
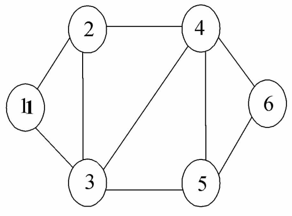

All request connections are reordered by MSF in step 1). We use the k-shortest paths algorithm in step 2) and step 3) to generate K candidate paths. From step 5) to step 8), we select a path that has the lowest indexed slot for a request from the set of candidate paths. In step 9) and step 10), the requests are grouped to eliminate partially the GFSs if the optical spectrum paths, in which r_i and r_{num} are carried, have common links and the optical spectrum paths are only separated by GFSs. Note that all eliminated GFSs in step 9) may be used when selecting consecutive available FSs on each link along the path $p^j_{r_i}$ in step 5) to step 8) for remaining request connections from $i+1$ to $R-1$.

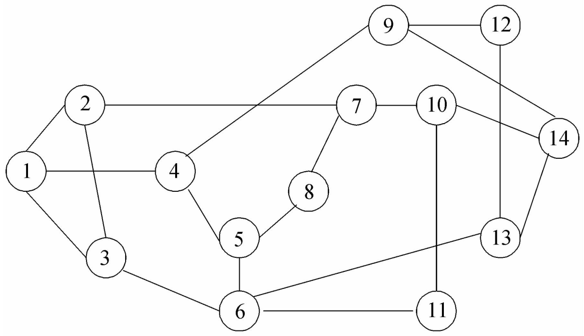
3 Performance evaluation

In this section, we present the simulation results of the proposed algorithms. In order to examine the performance of the TGMSF and TGLPF algorithms, we use the small topology (6 Nodes, 9 Links), moderate topology (14 Nodes, 21 Links) and large topology (19 Nodes, 40 Links) to evaluate the performance of FA-FF, MSF, LPF, TGMSF and TGLPF. Fig. 1 gives the three network topologies used. Let $K=3$ and guard-bands of GFSs=2 FSs. We assume that the fiber on each link is bidirectional and set FS=5 Gbps.

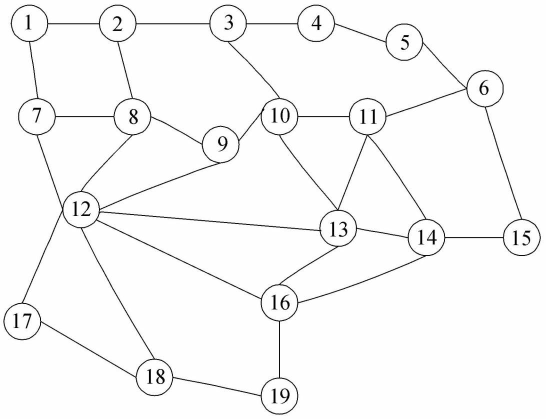
All connection requests of the source and destination pairs are generated uniformly over the set of nodes. The number of requested FSs, T_i, is uniformly distributed on {5, 10, 15, 20} Gbps. $|F|$ is used to denote the optimal number of FSs.



(a) Simple topology



(b) NSFNET



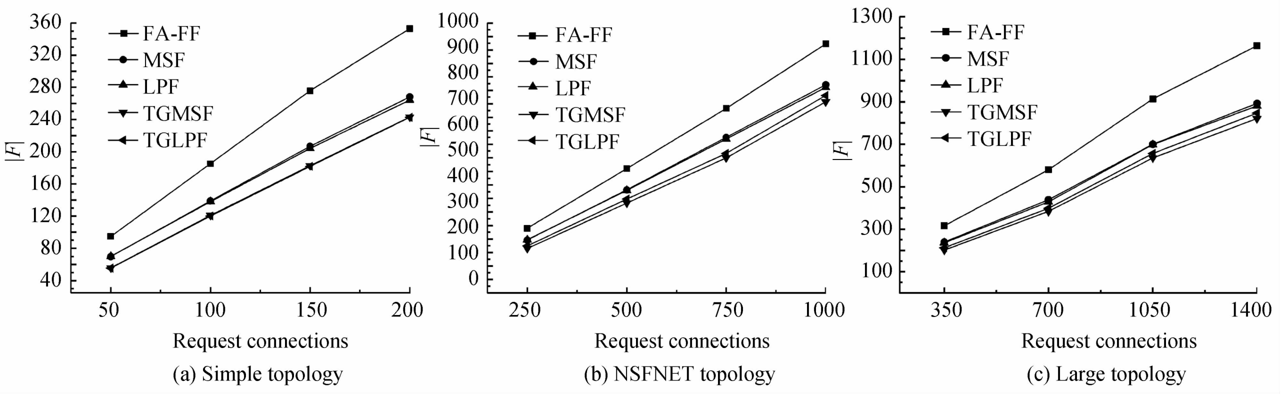
(c) Large topology

Fig. 1 Three network topologies

Fig. 2 shows the simulation results of the two proposed algorithms and other existing algorithms under different number of requests for the three network scenarios. For increasing the evaluation quality, the results are averaged over 1000 simulations, which means we get the value of each point in Fig. 2 by running the evaluation software 1 000 times. As the number of nodes in three network topologies varies, we should evaluate the algorithms in different scenarios to which the relevant numbers of requests are fed, ensuring that this comparison is relatively fair. Contrarily, the performance differences may be so small that it is hard to distinguish all fives algorithms if the inappropriate numbers of requests are small or very large.

We can see that, in all listed cases, TGMSF and TGLPF outperform the referenced algorithms. The gap between the MSF and LPF is small, which is in accordance with the conclusion made in Ref. [10-11]. It is also shown that FA-FF has the worst performance, since it used First-Fit spectrum assignment which tends to select the shortest path and not select the path with minimum FS index.

Fig. 2(a) shows that the two proposed algorithms have almost the same performance. We also see from Fig. 2(b) and Fig. 2(c) that TGMSF is a little better than TGLPF. Compared to FA- FF, LPF and MSF, Table 1 presents the reduction ratio of the number of



(a) Simple topology (b) NSFNET topology (c) Large topology

Fig. 2 FSs used versus number of requests for three topology

Table 1 Reduction ratio of the number of FSs for TGLPF/TGMSF

Items	Reduction (%)				
	Fig. 2(a)	Fig. 2(b)		Fig. 2(c)	
	TGLPF/TGMSF	TGLPF	TGMSF	TGLPF	TGMSF
FA-FF	45.9	26.4	30.0	(41.5#)/37.4	(44.9#)/42.1
MSF	11.6	5.5	8.5	(7.7#)/5.5	(10.2#)/9.1
LPF	9.5	3.8	6.8	(7.7#)/3.8	(10.2#)/7.3

#: the number of connections is 1000.

FSs for TGLPF/TGMSF when the number of request connections reaches maximally in each of three Figures, 200, 1 000 and 1 400, respectively.

We find that the resource utilization increases for the proposed algorithms when the number of nodes increases from 14 in Fig. 2(b) to 19 in Fig. 2(c). This conclusion is still valid even when the equal number of connections, 1000, is fed. In such a case, the averaged number of connections (or traffic volume) for each source-destination nodes pair in Fig. 2(c) is fewer than that in Fig. 2(b), so the performance of TGMSF in Fig. 2(c) is better than that of TGMSF in Fig. 2(b).

4 Conclusion

We have proposed two heuristic algorithms called TGMSF and TGLPF based on traffic grooming in EONs. Simulation results show that TGMSF and TGLPF improve the spectrum utilization well. However, the additional process of demodulation, electronic domain switching and remodulation makes the node implementation some complex. Therefore, there is a tradeoff between the implementation complexity and the spectrum efficiency. Besides, if we can select modulation levels according to transmission distance or adopt some intelligence algorithms like genetic algorithm, the spectrum utilization will be further improved.

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