Data-Oriented Malleable Reservation to Revitalize Spectrum Fragments in Elastic Optical Networks

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Abstract: This paper investigates malleable reservation (MR) for data-oriented requests to revitalize spectrum fragments in elastic optical networks. We formulate a mixed integer linear programming model and propose a time-efficient heuristic to solve the MR problem.

OCIS codes: (060.1155) All-optical networks; (060.4251) Networks, assignment and routing algorithms.

1. Introduction

As a promising physical infrastructure for the next-generation backbone networks, flexible-grid elastic optical networks (EONs) have the great potential to support a wide range of bandwidth-intensive applications that have diverse traffic characteristics and quality-of-service (QoS) requirements. Previously, people have studied numerous EON planning and provisioning schemes for flow-oriented requests (FO-Rs), including the scenarios such as immediate reservation (IR) [1,2] and advance reservation (AR) [3,4]. Basically, IR and AR only have different requirements on setup delay, but they both reserve fixed bandwidth for each request. Meanwhile, with the fast development of emerging applications, such as grid computing and data backup and migration, there are more and more data-oriented requests (DO-Rs) to be accommodated in backbone networks. Different from FO-Rs, DO-Rs usually need to accomplish timely bulk-data transfer but do not have rigid requirements on setup delay and transmission bandwidth. Recent studies have proposed to use adjustable spectrum allocation over time to accommodate time-varying traffic in EONs [5,6]. However, the proposals were still for FO-Rs and did not fully consider the characteristics of DO-Rs.

In this paper, we propose to accomplish efficient bulk-data transfer in EONs with data-oriented malleable reservation (MR). Specifically, we study how to effectively revitalize the spectrum fragments generated by FO-Rs to accommodate DO-Rs each of which has a certain amount of data to transfer. We enable spectrum retuning and transmission pausing for DO-Rs, and design the MR problem to maximize the average transmitted data of DO-Rs under the constraint that the maximum times of spectrum retuning is limited for each request. We formulate a mixed integer linear programming (MILP) model, propose a time-efficient heuristic to solve the problem, and verify their performance with simulations.

2. Data-Oriented Malleable Reservation to Revitalize Spectrum Fragments

We consider an EON whose topology is $G(V,E)$ with node and link sets as V and E, and assume that the operator performs MR over T, which is the set of discrete time slots (TS') that he/she can look ahead for scheduling DO-Rs. The set $\{C_{e,t} : e \in E, t \in T\}$ stores all the spectrum fragments generated by coexisting FO-Rs, and $C_{e,t}$ denotes the set of all the available channels, *i.e.*, the available frequency slot blocks (FS-blocks), on the fiber link $e \in E$ during the t-th TS. The size of the i-th channel on link e during t is $w_{e,t}^{(i)}$, in number of frequent slots (FS'). Note that with an empty link, we can enumerate all the possible channels on it, from those that each occupies one FS to the one that covers all the FS'. Hence, if we mark each possible channel with a unique index, we can identify a particular channel's size and spectral location. Here, for the i-th available channel on link e during t, we define its unique index as $\pi_{e,t}^{(i)}$. The set of DO-Rs to be scheduled in the EON is D, in which the r-th DO-R is represented by a tuple $(s^{(r)}, d^{(r)}, \mathscr{F}^{(r)}, t_a^{(r)}, d_{max}^{(r)})$, where $s^{(r)}$ and $d^{(r)}$ are the source and destination, $\mathscr{F}^{(r)}$ is the size of the data to transfer (in terms of the usage of FS' over TS'), $t_a^{(r)}$ is the arrival TS, and $d_{max}^{(r)}$ is the longest look-ahead period to coordinate the request's data transfer.

With the network model above, we can define the data-oriented MR problem as to perform changeable routing and spectrum assignment (RSA) over time for all the DO-Rs with the objective to maximize the average transmitted data. Basically, since the look-ahead period for handling the r-th DO-R is limited by $d_{max}^{(r)}$, it is possible that the data transfer cannot be fully accomplished in the current provisioning batch. To measure the effectiveness of MR algorithms, we define $\eta^{(r)}$ as the percentage of the transmitted data of the r-th DO-R. Note that in between any two consecutive TS' t and $t+1$, if the RSA of a DO-R is changed, the DO-R experiences a RSA reconfiguration. As RSA reconfigurations introduce increased operational complexity and cost, we limit the reconfiguration times below Q for each DO-R.

We first formulate a link-based MILP model to tackle the MR problem. The additional notations of the parameters and decision variables are as follows. O_v: set of links that origin from node $v \in V$; I_v: set of links that end at node $v \in V$; $V^{(r)}$: set of all the intermediate nodes used for the r-th DO-R; $T_m^{(r)}$: set of TS' that MR uses for the r-th DO-R; $T_q^{(r)}$: set of TS' that each can be possibly after a RSA reconfiguration of the r-th DO-R; $x_{e,t}^{i,r}$: boolean variable that equals 1 if the i-th channel on link e during t is assigned to the r-th DO-R, otherwise it equals 0; $\phi_t^{(r)}$: boolean variable that equals 1 if there is a RSA reconfiguration in between $t-1$ and t for the r-th DO-R, otherwise it equals 0.

Objective:

$$Maximize \quad \frac{1}{|D|}\sum_{r\in D}\eta^{(r)}, \tag{1}$$

where $|D|$ is the number of DO-Rs in the network.

Constraints:

$$\sum_{e\in I_{s^{(r)}}}\sum_{i\in C_{e,t}} x_{e,t}^{i,r}\le 0,\forall r,t\in T_m^{(r)} \quad (2) \qquad \sum_{e\in I_{d^{(r)}}}\sum_{i\in C_{e,t}} x_{e,t}^{i,r}\le 1,\forall r,t\in T_m^{(r)} \quad (3) \qquad \sum_{e\in I_v}\sum_{i\in C_{e,t}} x_{e,t}^{i,r}\le 1,\forall r,t\in T_m^{(r)},v\in V^{(r)} \quad (4)$$

$$\sum_{e\in O_{s^{(r)}}}\sum_{i\in C_{e,t}} x_{e,t}^{i,r}\le 1,\forall r,t\in T_m^{(r)} \quad (5) \qquad \sum_{e\in O_{d^{(r)}}}\sum_{i\in C_{e,t}} x_{e,t}^{i,r}\le 0,\forall r,t\in T_m^{(r)} \quad (6) \qquad \sum_{e\in O_v}\sum_{i\in C_{e,t}} x_{e,t}^{i,r}\le 1,\forall r,t\in T_m^{(r)},v\in V^{(r)} \quad (7)$$

Eqs. (2) - (7) ensure that the assigned channel (*i.e.*, FS-block) of each DO-R is on the fiber links that are in the right direction, *i.e.*, $s^{(r)}\to d^{(r)}$, and one DO-R occupies at most one channel during a TS.

$$\sum_{e\in O_v}\sum_{i\in C_{e,t}} x_{e,t}^{i,r}\cdot\pi_{e,t}^{(i)}=\sum_{e\in I_v}\sum_{i\in C_{e,t}} x_{e,t}^{i,r}\cdot\pi_{e,t}^{(i)},\forall r,t\in T_m^{(r)},v\in V^{(r)} \quad (8) \qquad \sum_{r\in D} x_{e,t}^{i,r}\le 1,\forall e,t,i\in C_{e,t} \quad (9) \qquad \sum_{t\in T_q^{(r)}}\phi_t^{(r)}\le Q,\forall r \quad (10)$$

Eqs. (8) and (9) ensure that the spectrum continuous and non-overlapping constraints are satisfied during each TS, respectively, while Eq. (10) makes sure that the maximum RSA reconfiguration times of each DO-R is within Q.

$$\phi_t^{(r)}\ge\begin{cases} x_{e,t}^{i,r}-x_{e,t-1}^{j,r},\forall r,e,t\in T_q^{(r)},i\in C_{e,t},\pi_{e,t}^{(i)}=\pi_{e,t-1}^{(j)} \\ x_{e,t}^{i,r},\forall r,e,t\in T_q^{(r)},i\in C_{e,t},\pi_{e,t}^{(i)}\notin\{\pi_{e,t-1}^{(j)}:j\in C_{e,t-1}\}\end{cases} \quad (11) \qquad \eta^{(r)}\le\frac{\sum_{t\in T_m^{(r)}}\sum_{e\in O_{s^{(r)}}}\sum_{i\in C_{e,t}} x_{e,t}^{i,r}\cdot w_{e,t}^{(i)}}{\mathscr{F}^{(r)}},\forall r \quad (12)$$

Eq. (11) decides whether a RSA reconfiguration is needed for a DO-R, and Eq. (12) calculates the value of $\eta^{(r)}$.

Due to its complexity, the MILP can become intractable when the EON has large size and/or there are a lot of DO-Rs to be served. Moreover, the MILP can only provide optimal solutions for the static network scenario, where all the FO-Rs have been served in advance and the leftover network spectra for DO-Rs will not change. However, in practice, the network scenario can be dynamic, as FO-Rs and DO-Rs can come and leave on-the-fly. In order to address the dynamic network scenario, we propose the following heuristic, namely, minimum-transferred-data-guaranteed MR (MTDG). Note that considering the QoS requirements of FO-Rs, we provide them with a higher priority in provisioning such that at each TS, FO-Rs are served first and DO-Rs only utilize the spectrum fragments left by them.

Step 1: For each s - d pair, pre-calculate K-shortest routing path candidates.

Step 2: At each TS, sort the pending DO-Rs including both the old and the new ones in descending order of their average amounts of data that is expected to be transferred per TS before their deadlines.

Step 3: Perform RSA, *i.e.*, find the routing path and available channel in the current TS t for the DO-Rs one by one. For each DO-R r, we define its number of remaining RSA reconfiguration times as $q^{(r)}$, *i.e.*, $q^{(r)}\in[0,Q]$. Then, at the beginning of TS t, if $q^{(r)}<d_{max}^{(r)}-(t-t_a^{(r)})$ (*i.e.*, the number of remaining RSA reconfiguration times is less than the remaining TS' for data transfer), we first check whether its RSA for TS $t-1$ is still available; if yes, we keep to use it to avoid reconfiguration. Otherwise, we find the largest available channel over all the path candidates and check whether the channel's size can satisfy a preset threshold γ, which is the minimum percentage of total data to be transferred per TS; if yes, we conduct a RSA reconfiguration to use the new channel; otherwise, we pause the data transfer of the DO-R and wait for the next TS. On the other hand, if $q^{(r)}\ge d_{max}^{(r)}-(t-t_a^{(r)})$, which means that the constraint on RSA reconfiguration times is not an issue any more, we just choose the largest available channel over all its path candidates for the DO-R.

Step 4: Determine the DO-Rs that still need to be taken care of in the next TS. For each DO-R r, if all its data has been transferred, or the RSA reconfiguration times has been used up, or its deadline $d_{max}^{(r)}$ has been reached, the MR for it will not be carried on for the next TS.

Step 5: Repeat **Steps 2 - 4** until the duration (i.e., T) of the current provisioning batch expires.

3. Simulation Results and Discussion

We first perform simulations with static network scenario to compare the performance of MILP and MTDG, which run on a PC with 2.93 GHz Intel Core i3 CPU and 6 GB RAM. We use GLPK to solve the MILP model and use MATLAB R2013a to implement MTDG. In order to obtain optimum solution in a limited amount of time, the 4-node topology in Fig. 1 is used, where each fiber link has 5 FS'. The FO-Rs are generated with an IR-and-AR mixed traffic model, and served with shortest-path routing and first-fit spectrum assignment (SPR-FFSA) in advance to generate time-varying network spectrum utilization over the period $[1,30]$ TS'. For each DO-R r, its $s^{(r)}$-$d^{(r)}$ pair is randomly chosen, the arrival time $t_a^{(r)}$ is uniformly distributed with $[15,21]$ TS', and the longest look-ahead period $d_{max}^{(r)}$ is uniformly distributed with $[3,5]$ TS'. The number of maximum RSA reconfiguration times is set as $Q = 1$.

Table 1 shows the simulation results for $|D| = 1,2,3$. For MTDG, $\gamma = 0$ means that there is no preset size-threshold for channel selection, while $\gamma = 0.6$ means that when $q^{(r)} < d_{max}^{(r)} - (t - t_a^{(r)})$, the selected channel's size has to be able to accommodate at least 60% of the average amount of data that is expected to be transferred per TS. We can see that MTDG with $\gamma = 0$ achieves similar results on $\eta^{(r)}$ as the MILP, while its average running time is significantly less. However, when $\gamma = 0.6$, MTDG returns much worse results on $\eta^{(r)}$, due to the constraint for channel selection.

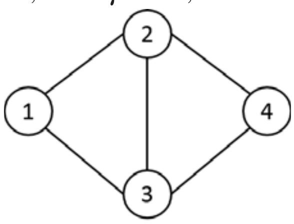
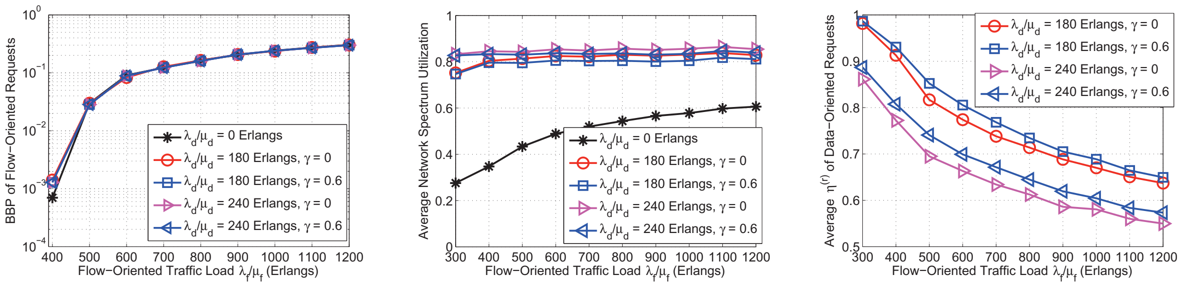


Fig. 1. 4-node topology.

$\|D\|$	Average $\eta^{(r)}$			Average Running Time (Seconds)		
	MILP	MTDG		MILP	MTDG	
		$\gamma = 0$	$\gamma = 0.6$		$\gamma = 0$	$\gamma = 0.6$
1	1.0000	1.0000	0.4190	0.9495	0.1160	0.0867
2	0.8553	0.8260	0.5161	2.8018	0.0960	0.0945
3	0.7911	0.7220	0.4709	2063.4654	0.1363	0.1004

Table 1. Results from simulations with static network scenario.

We then conduct simulations for dynamic network provisioning with a larger network topology (*i.e.*, 14-node NSFNET) to evaluate the performance of MTDG further. FO-Rs are still generated and served similarly as mentioned above. DO-Rs also become dynamic and are generated according to the Possion process. The maximum RSA reconfiguration times Q is set to 5. Fig. 2(a) shows the results on FO-Rs' bandwidth blocking probability (BBP), when the traffic load of DO-Rs is 0, 180 and 240 Erlangs. It can be seen that FO-Rs' BBP results stay almost unchanged when the traffic load of DO-Rs increases. This observation verifies that the proposed MTDG algorithm for MR can effectively revitalize the spectrum fragments in EONs, which are generated by FO-Rs, for bulk-data transfer. More importantly, the provisioning of DO-Rs will not affect the service of FO-Rs. Fig. 2(b) illustrates the results on average network spectrum utilization, which indicate that the injection of DO-Rs brings significant improvements on spectrum utilization. Again, these results confirm that the spectrum fragments are effectively recycled. The results on the average percentage of transmitted data of DO-Rs are plotted in Fig. 2(c). It is interesting to notice that for the dynamic provisioning, MTDG with $\gamma = 0.6$ always achieves larger average $\eta^{(r)}$ than the one with $\gamma = 0$. This is because in the dynamic provisioning, the network spectrum utilization can change dramatically over time and since MTDG with $\gamma = 0.6$ tends to choose larger spectrum fragments in future TS', it makes the data transfers more effective. Hence, when choosing γ for MTDG, we should carefully consider the change of network spectrum utilization in EONs.



(a) (b) (c)

Fig. 2. Results from simulations with dynamic network provisioning.

4. Conclusion

We formulated an MILP model and proposed an efficient heuristic for efficient bulk-data transfer in EONs with data-oriented MR. Simulation results verified that the proposed algorithms could effectively revitalize the spectrum fragments in EONs, and improve network spectrum utilization significantly without affecting the provisioning of FO-Rs.

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