Spectrum Trading between Virtual Optical Networks Embedded in an Elastic Optical Network

Shifeng Ding¹, Xiaodong Fu², Boping Jiang², Sanjay K. Bose³, Gangxiang Shen¹*,

¹School of Electronic and Information Engineering, Soochow University, Suzhou, Jiangsu Province, P. R. China
²Zhongtian Broadband Technology, Rudong, Jiangsu Province, P. R. China
³Department of Electrical and Electronic Engineering, IIT Guwahati, Guwahati, INDIA
*Corresponding e-mail address: shengx@suda.edu.cn

Abstract: We propose a spectrum trading (ST) scheme to trade spectra between virtual optical networks embedded in an elastic optical network (EON) for efficient spectrum utilization and better client quality of service. An integer linear programming (ILP) model and a heuristic algorithm are developed. Results show the effectiveness of the proposed scheme. © 2019 The Author(s)

OCIS codes: (060.4250) Networks; (060.4256) Network, network optimization

1. Introduction

With the fast growth of Internet traffic, the optical transport network typically functioning as a backbone is required to efficiently carry user traffic demands. For this, network virtualization [1-2] has been considered as an effective practical solution to improve optical network capacity utilization. Network virtualization splits the capacity of a physical optical network into multiple independent virtual optical networks (VONs) for different clients. Once a VON is embedded or established, its assigned capacity is generally fixed during its contract period. However, the traffic demand on a VON is not static but keeps on changing. Because of this, in some period, there may be large idle capacity on some virtual links of a VON when its traffic demand is low, while in another period, the VON may be short of capacity on some virtual links when its traffic demand is high. Current VON embedding techniques cannot resolve this for real-time traffic fluctuations.

To overcome the above issue, we propose a novel scheme called spectrum trading (ST) that allows different VONs to trade their capacity according to their actual real-time capacity requirements. Specifically, a VON may assign its idle capacity to another VON that requires more capacity in the current period, and expect that in the future, the latter can return this capacity to the former if the traffic demand situation reverses. To evaluate the benefit of the proposed scheme, we formulate the ST problem as an integer linear programming (ILP) model given a set of VONs embedded in an EON. We also develop an efficient heuristic algorithm for spectrum trading between different VONs. Simulation results show the effectiveness of the proposed ST scheme.

2. Spectrum trading between virtual optical networks embedded in an elastic optical network

The ST scheme essentially aggregates the spectrum resources on each VON to form a resource pool and all the involved VONs can share to use idle resources in the pool. This is expected to significantly improve the overall spectrum utilization. To enable spectrum trading between VONs, we first divide the lifecycle of each VON into several time slots. In each time slot, virtual links that have idle capacity in terms of frequency slot (FSs) can trade these idle FSs with virtual links that are short of capacity if these virtual links share common physical link(s). For a VON that provides capacity for use by other VONs, it is assigned a positive credit according to the amount of capacity that it provides. Also, for a VON that uses the capacity provided by other VONs, we assign a negative credit according to the amount of capacity that it uses. Moreover, to avoid the situation of a selfish client which only wishes to use other’s resources, while not sharing its resources with others, we set a bound on the above credit. A client whose accumulated credit is smaller than a certain negative threshold is prevented from further using others’ resources.

Fig. 1 shows an example for the ST scheme. Virtual optical networks VON1 and VON2 are embedded in the same physical network, where virtual links b1-c1 and b2-d2 correspond to lightpaths B-C and B-C-D. The two virtual links share common physical link B-C, on which we may trade spectra between the two VONs according to their traffic status. We use \((F, t)\) to denote the real-time capacity requirement on a virtual link, where \(F\) is the number of FSs required and \(t\) is the time slot index. For example, \((2, T1)\) in Fig. 1 means that 2 FSs are required in time slot \(T1\). The
spectral usage status of physical link B-C is shown at the bottom right corner of Fig. 1. Initially, in time slot $T_0$ (after virtual network embedding), virtual links b1-c1 and b2-d2 are both assigned with 3 FSs. In time slot $T_1$, the actual number of FSs required by virtual links b1-c1 and b2-d2 are 2 and 4, respectively. For the scenario without spectrum trading, 25% traffic on virtual link b2-d2 will be blocked because of insufficient link capacity. However, with spectrum trading, virtual link b2-d2 can borrow 1 FS from virtual link b1-c1 to accommodate its traffic since the latter currently has low traffic demand and therefore 1 idle FS. Similarly, in time slot $T_2$, the number of FSs required on virtual links b1-c1 and b2-d2 are 5 and 1, respectively. Without spectrum trading, 40% traffic on virtual link b1-c1 will be blocked. However, with spectrum trading, virtual link b1-c1 can borrow 2 FSs from virtual link b2-d2, which ensures that no traffic is lost. In this example, the overall spectrum utilization of physical link B-C in time slots $T_1$ and $T_2$ are improved by (12-9)/12=25%.

In the above trading process, in order to value the contribution made by each VON that provides resources for other VONs to use, we define a credit parameter $\phi_{v,t}$ to denote the contribution of VON $v$ in time slot $t$. This parameter is negative if a VON borrows resources from other VONs. In Fig. 1, in time slot $T_1$, the credit of VON1 is $\phi_{VON1,T_1} = 1$, while the credit of VON2 is $\phi_{VON2,T_1} = -1$ since the former lends 1 FS to the latter. Similarly, in time slot $T_2$, the credit of VON1 is $\phi_{VON1,T_2} = -2$, while the credit of VON2 is $\phi_{VON2,T_2} = 2$ since the latter lends 2 FSs to the former. We also define a cumulative credit parameter for each VON as $\gamma_{v,T} = \sum_{t=1}^{T} \phi_{v,t}$, which is the cumulative value function (CVF) of $\phi_{v,t}$ summed over all the time slots up to $T$. In Fig. 1, it is easy to find that $\gamma_{VON1,T_2} = -1$ and $\gamma_{VON1,T_2} = 1$. This cumulative credit can help maintain the fairness among VONs to prevent a VON from being selfish. Specifically, if $\gamma_{v,T} < \mu$ in time slot $T$, we would stop VON $v$ from borrowing any resource from any other VONs, where $\mu$ is a pre-decided threshold for a VON to stop borrowing resources.

3. Problem statement, ILP model, and heuristic algorithm

For the above ST scheme, we need to efficiently trade spectrum resources between different VONs in different time slots to maximize the overall spectrum utilization and quality of service provisioned for each VON. We define this optimization problem as follows. We are given a set of VONs, in which each VON has a pre-determined topology and each of its virtual links is assigned a specific set of FSs denoted as $C(v, s, d, x, y)$, where $v$ is the index of a VON that the virtual link is associated with, $s, d$ are the source and destination nodes of the virtual link, and $x, y$ are the starting and ending FS indexes of the spectrum assigned to the virtual link in VON’s contract period. The route traversed by each virtual link in the physical topology is pre-determined, which is obtained from a virtual network embedding (VNE) process [1]. At the same time, we are also given the actual bandwidth requirements on each virtual link of a VON in different time slots, which is denoted as $R(v, s, d, t, F_t)$ where $t$ is the index of the time slot and $F_t$ denotes the number of FSs actually required to accommodate all the user’s traffic demand on the virtual link in time slot $t$. Our objective is to maximize the amount of traffic demand that can be supported by the VONs in different time slots.

We need to consider the constraints of limited spectrum resources assigned to each VON and the overlapping relation between the virtual links of different VONs on common physical links.

We have formulated the optimization problem as an ILP model. However, due to the page limit, we do not present its mathematical formulae, but explain its constraints in plain text. They include: (1) A virtual link uses its own FSs to carry its own traffic demand at the first place. (2) A virtual link cannot use an FS if it is not owned by any VON. (3) The number of FSs that a virtual link borrows should not exceed its need. (4) The spectrum assigned for two virtual links should not overlap if their mapped physical routes share common link(s). (5) A VON cannot borrow any FS from other VONs in subsequent time slots if its cumulative credit is negative and smaller than the threshold $\mu$ mentioned earlier. The above ILP model can find an optimal solution for the ST scheme but is NP-hard. Therefore, for a large-size network, we also develop an efficient heuristic algorithm as shown in Fig. 2. This algorithm considers each time slot to implement spectrum trading between VONs, where we use the idle capacity on other virtual links to increase the capacity of a virtual link so as to help accommodate its unserved traffic demand on a best-effort basis.

---

**Heuristic algorithm for Spectrum Trading**

**Step 1:** Use the capacity assigned to each virtual link of a VON to carry its traffic demand;

**Step 2:** Sort all the virtual links in a descending order based on the amounts of traffic demands that cannot be accommodated using their own capacities; the ordered list is denoted as $L$;

**Step 3:** Get the first virtual link $l$ from $L$; if the cumulative credit of its corresponding VON is not smaller than a preset negative threshold, go to Step 4; otherwise, go to Step 5;

**Step 4:** Borrow unused capacity on other virtual links to accommodate the unserved traffic demand of virtual link $l$ at the best effort through spectrum trading; update the cumulative credits for all the related VONs in the trading process;

**Step 5:** If not all the links in $L$ have been considered, then get the next virtual link $l$ from $L$, go back to Step 4; otherwise, go to Step 6;

**Step 6:** Stop the traffic demand provisioning process and output the results.

Fig. 2. Heuristic algorithm for spectrum trading.
4. Simulations and results
We employed a 6-node, 8-link (n6s8) network and the 15-node, 21-link NSFNET network as test networks [3] to evaluate the performance of the proposed ST scheme. The link distance set for each link in units of km is employed to decide the modulation format used for each lightpath according to the transparent reach table in [3]. We assumed that there are 8 VONs and their lifecycles are the same and are uniformly divided into 4 time slots. The numbers of virtual nodes and virtual links belonging to each VON are randomly generated within the ranges of \([N/2, N]\) and \([L/2, L]\) respectively, where \(N\) and \(L\) are the numbers of physical network nodes and links, respectively. The capacity assigned to each virtual link in a VON is decided based on a traffic demand matrix between node pairs, in which each node pair has the same average traffic demand with an intensity selected from the set \(X \in \{40, 60, \cdots, 140\} \) Gb/s. The actual traffic demands on each virtual link in different time slots are randomly generated within the range of \([10, 2X-10]\) Gb/s. To enable more flexible spectrum trading, we also assume that the scheme of Split Spectrum [4] is employed to allow a virtual link to use the bandwidth of multiple non-neighboring sub-bands along its physical route. Here the maximum number of Split Spectrum sub-bands is 2 for the ILP model to avoid computational difficulty, while there is no such constraint for the heuristic algorithm. The cumulative credit threshold \(\mu\) that prevents a VON from borrowing FSs from other VONs is set to be \(\mu = -10\).

Fig. 3 compares the amount of overall traffic demand that is actually carried by the VONs under different average traffic demands in the n6s8 network, where legends “Non_ST,” “Heu_ST,” and “ILP_ST” correspond to the result without ST, and the results of the heuristic algorithm and the ILP model with ST. We see that the case with ST can carry more traffic demand than the case without ST. Moreover, with the increase of the average traffic demand, the difference between the cases with and without ST become more significant. This is because a larger average traffic demand corresponds to a larger fluctuation of actual traffic demand. This enables more opportunity for the ST scheme to play its role in improving capacity utilization by trading spectrum resources between VONs. We can see that when the average traffic demand is 70 Gb/s, the difference between the cases with and without ST is large enough to be more than 20%. In addition, comparing the results of the heuristic algorithm and the ILP model, we see that the heuristic algorithm is efficient to perform very close to the ILP model. A similar study was carried out for the NSFNET network and the results are shown in Fig. 4. The curve of “IR” shows the improvement ratio by the ST scheme over the case without ST. We can see that the ST scheme can perform better with an increasing average traffic demand, by more than 15%. Based on the results of the heuristic algorithm, Fig. 5 shows the impact of the cumulative credit threshold on the performance improving ratio by the ST scheme. We can see that with the increase of the threshold, the improvement ratio increases for both networks. However, this improvement saturates for a large cumulative credit threshold, implying that a small credit threshold may be sufficient to give good performance and prevent selfishness.

5. Conclusion
We proposed an ST scheme that allows VONs to trade their spectrum resources according to their actual traffic demands in different time slots. An ILP model and an efficient heuristic algorithm were developed to assign the resources for trading in different time slots and to validate the performance of the proposed scheme. Simulation results show the effectiveness of the proposed scheme, which can significantly increase carried traffic demands by VONs.

6. References