Optimal Time-dependent Spectrum Sharing between Neighboring Channels in Elastic Optical Networks

Xiaowei Zhao[1], **Gangxiang Shen**[1], **and Sanjay K. Bose**[2]

[1]School of Electronic and Information Engineering, Soochow University, Suzhou, Jiangsu, China
[2]Department of EEE, Indian Institute of Technology, Guwahati, India

Abstract— Considering the time-dependent bandwidth characteristic of elastic optical networks, we develop two ILP models to assign spectra for lightpaths in a general mesh-network so as to maximally share optical spectra between neighboring channels and therefore minimize the total required spectrum in the whole network.

1. INTRODUCTION

In recent years, the rapid growth of high-bit-rate applications such as cloud computing and multimedia video services has led to a tremendous increase in the volume of Internet traffic. It has therefore become important to design very efficient and flexible networks which will perform better than the traditional ITU-T [1] based Wavelength Division Multiplexing (WDM) optical networks. A typical WDM optical network used for optical communications is inflexible and inefficient because of its fixed grid and coarse granularity. Elastic optical networks based on the Orthogonal Frequency Division Multiplexing (OFDM) technology can solve most of these problems and are considered promising for next-generation optical networking. The elastic optical transmission technique allows flexible bandwidth and spectrum allocation [2] along with efficient spectrum utilization. This adapts well to real networks where the traffic demand changes dynamically in different time periods. In [3], the authors proposed the concept of time-dependent optical spectrum sharing which adapts elastic optical channels to carry time-dependent traffic demands. In [4], we had applied this concept to a single fiber link and our simulation studies showed that elastic optical channels can successfully handle the time-dependent uncertainty of traffic demand on each optical channel while still achieving high spectrum efficiency.

This paper extends the concept of time-dependent optical spectrum sharing to a general mesh-network. We present two different ILP optimization models from different perspectives for efficiently assigning spectra for lightpaths in a general mesh-network so as to achieve high spectrum efficiency in supporting time-dependent traffic demands. When assigning spectra for lightpaths, one model considers a fixed center frequency of each lightpath between SD pairs in all the time slots, while the other does not consider such a constraint. The tradeoff between them is that the model with a fixed center frequency can make the reconfiguration of lightpaths simpler as we do not need to change the channel center frequency from time slots to time slots, while it may suffer from poorer spectrum utilization compared to the case without such a constraint. Both optimizations have the same objective to minimize the maximal index of the used frequency slots (FSs) on the fiber links in the entire network where we assume that the time-dependent traffic demand of each lightpath between SD pairs is given in advance.

2. CONCEPT OF TIME-DEPENDENT SPECTRUM ALLOCATION

Based on time-dependent optical spectrum sharing, we can allocate the bandwidth or spectrum of each lightpath according to the actual channel traffic demand at different time periods to better utilize the spectrum [5]. We illustrate the concept of time-dependent spectrum allocation in Fig. 1, where we show the changes in the spectrum allocation for two neighboring optical channels between two consecutive time slots. In time slot $t1$, optical channel $f1$ has more traffic demand, thereby requiring more spectra, while optical $f2$ has less traffic demand, thereby requiring fewer spectra. Similarly, in time slot $t2$, due to the change of traffic demand on each the two channels, optical channel $f1$ may require fewer spectra while optical channel $f2$ may require more spectra. This implies that we can arbitrarily allocate spectrum between the two neighboring optical channels, when the sum of the spectra used by the two channels does not exceed the total spectrum between their central frequencies. With this spectrum sharing, elastic optical networks are expected to achieve good optical spectrum utilization and efficiency. We found that the efficiency of the above spectrum sharing is closely related to the complementary status of the traffic demands of the two neighboring channels in different time slots. If the two channels complement each other, we could assign a smaller amount of joint spectrum for them. On the contrary, if the channels always reach their peak traffic demands simultaneously or if the variation patterns of their traffic demands are always in line, there is no advantage of spectrum sharing as described above.

For a general mesh-network based on the elastic OFDM technology, with the constraints of *spectrum consecutiveness* and *spectrum continuity*, it is important to properly arrange the spectrum of each lightpath between SD pairs according to their individual time-dependent traffic demand distributions so as to achieve the best spectrum sharing. This is the key research problem that we aim to address and optimize in this paper.

3. ILP MODELS FOR SPECTRUM ASSIGNMENT IN GENERAL MESH-NETWORKS

For optimal assignment of spectrum in a general mesh-network, we develop two ILP models to minimize the total required spectrum subject to the condition that all the time-dependent channel bandwidths are satisfied. The first ILP model keeps fixed center frequencies for each lightpath between SD pairs which may be allowed to shrink its assigned bandwidth at a certain maximal percentage (for the situation where there is insufficient spectrum and therefore bandwidth squeezing [6] is required for the lightpath between a SD pair). Note that this model is generic, which by default can also be used to design for the case that does not allow for bandwidth shrinking. The second ILP model is one where the center frequencies are not fixed for each lightpath between SD pairs.

3.1. ILP Model with Fixed Channel Center Frequency

Sets and Parameters: $\mathbf{V}$ is the set of network nodes. $\mathbf{L}$ is the set of network links. $\mathbf{NP}$ is the set of SD pairs in the network. $\mathbf{T}$ is the set of the time slots. $\mathbf{R_{sd}}$ is the set of routes for a SD pair in the network. TD_{sd}^t is the number of FSs (i.e., bandwidth) required between SD pair sd at time slot t. $X_{ij}^{sd,r}$ is a binary parameter that takes the value of 1 if the lightpath route r between SD pair sd traverses link ij; 0, otherwise. α is the percentage that is maximally allowed for bandwidth squeezing for each lightpath. Δ is a large value.

Variables: f_{sd} is an integervariable denoting the center FS index (i.e., center frequency) of the lightpath between SD pair sd. S_{sd}^t is an integer variable denoting the starting FS index of the lightpath between SD pair sd at time slot t. E_{sd}^t is an integer variable denoting the ending FS index of the lightpath between SD pair sd at time slot t. y_{sd}^r is a binary variable that takes the value of 1 if the lightpath between SD pair sd chooses route r; 0, otherwise. δ_{sd2}^{sd1} is a binary variable that takes the value of 1 if the starting FS index S_{sd1}^t of the lightpath between SD pair $sd1$ is smaller than the starting FS index S_{sd2}^t of the lightpath between SD pair $sd2$ at any time slot; 0, otherwise. Note that this notation makes sense only when two different lightpaths share at least one common link. c is the maximal index of used FSs on the fiber links in the entire network.

The **objective** of the ILP model is to minimize the maximal index of the used FSs in the entire network, i.e., c, and the **constraints** of the model are as follows:

$$\delta_{sd2}^{sd1} + \delta_{sd1}^{sd2} = 1 \quad \forall sd1,\, sd2 \in \mathbf{NP},\, sd1 \neq sd2 \tag{1}$$

$$E_{sd2}^t - S_{sd1}^t \leq \Delta \cdot \left(\delta_{sd2}^{sd1} + 2 - X_{ij}^{sd1,r1} - X_{ij}^{sd2,r2} + 2 - y_{sd1}^{r1} - y_{sd2}^{r2}\right)$$
$$\forall ij \in \mathbf{L},\, sd1,\, sd2 \in \mathbf{NP},\, sd1 \neq sd2,\, r1,\, r2 \in \mathbf{R_{sd}} \tag{2}$$

$$\sum\nolimits_{r \in \mathbf{R_{sd}}} y_{sd}^r = 1 \quad \forall sd \in \mathbf{NP} \tag{3}$$

$$S_{sd}^t = f_{sd} - 0.5 \cdot TD_{sd}^t \cdot (1-\alpha) \quad \forall sd \in \mathbf{NP}, t \in \mathbf{T} \tag{4}$$

$$E_{sd}^t = f_{sd} + 0.5 \cdot TD_{sd}^t \cdot (1-\alpha) \quad \forall sd \in \mathbf{NP},\, t \in \mathbf{T} \tag{5}$$

$$f_{sd} \geq 0.5 \cdot TD_{sd}^t \cdot (1-\alpha) \quad \forall sd \in \mathbf{NP},\, t \in \mathbf{T} \tag{6}$$

$$c \geq E_{sd}^t \quad \forall sd \in \mathbf{NP},\, t \in \mathbf{T} \tag{7}$$

$$c \geq \sum\nolimits_{sd \in \mathbf{NP}, r \in \mathbf{R_{sd}}} TD_{sd}^t \cdot (1-\alpha) \cdot X_{ij}^{sd,r} \cdot y_{sd}^r \quad \forall ij \in \mathbf{L}, t \in \mathbf{T} \tag{8}$$

Constraints (1) and (2) ensure that the spectra of two lightpaths that share common links must not overlap. Constraint (3) ensures that there is only a single route used for lightpath establishment between SD pair. Constraints (4), (5) and (6) tell the relationship of the center FS index, the starting FS index, and the ending FS index of each lightpath at time slot t (with a certain bandwidth squeezing ratio). Constraint (7) ensures that the network-wide maximal FS index c is always no smaller than the ending FS index of any lightpath. Constraint (8) is a redundant one helping reduce the feasible solution region of the ILP model.

3.2. ILP Model with Non-fixed Channel Center Frequency

We have also developed an ILP model for the case that the channel center frequency is not fixed in different time slots. The model is extended from the one developed in [5] with the constraints and traffic demands satisfied in each time slot. Due to the page limit, we do not give the detail of the model here.

4. RESULTS AND PERFORMANCE ANALYSES

To evaluate the performance of the two ILP models, we assign spectra for the lightpaths in the SmallNet (10 nodes and 22 links) and COST 239 (11 nodes and 26 links) networks. We assume that for each lightpath between SD pairs, random hourly traffic demands (for 24 hours) are given. The traffic demand on each lightpath is assumed to vary in units of FSs, but within a certain maximal range. Specifically, we consider five ranges, from 1 to 10, 1 to 20, and maximally 1 to 50 (each number is even) units of FSs. We choose one route from multiple route options for each node pair to establish lightpaths. We minimize the total required spectra (without considering guard band) when all the time-dependent traffic demands are satisfied. In addition, for the bandwidth squeezing case, we employ the ILP model with fixed channel center frequency to minimize the total required spectra under different maximal bandwidth squeezing ratios. For this case, the required bandwidth on each lightpath between SD pairs is assumed to vary within a range from 1 to 20 units of FSs (each number is even).

Without considering bandwidth squeezing, Figs. 2 and 3 show the total number of FSs required in the SmallNet and COST239 networks with the increase of average bandwidth requirement of each lightpath, respectively. Comparing the results *with* and *without* fixed channel center frequency (i.e., "ILP 1" versus "ILP 2"), we can see that the case without fixed channel center frequency shows better performance, requiring much smaller numbers of FSs. This is reasonable since the spectrum

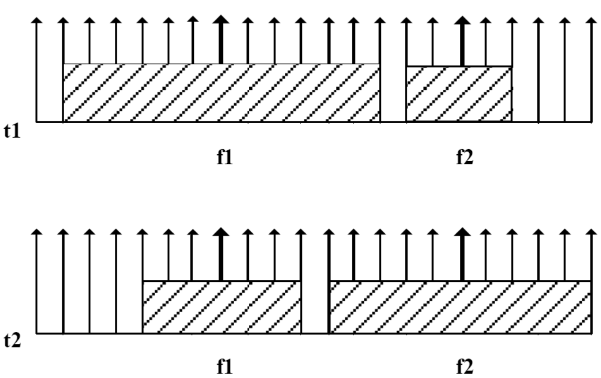

Figure 1: Time-dependent spectrum sharing between two neighboring optical channels.

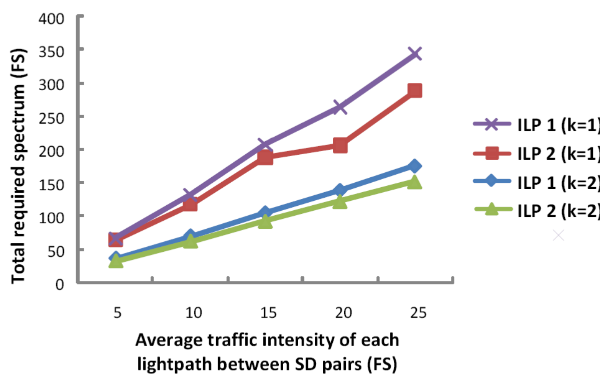

Figure 2: Total required spectra versus traffic demand intensities per node pair (SmallNet).

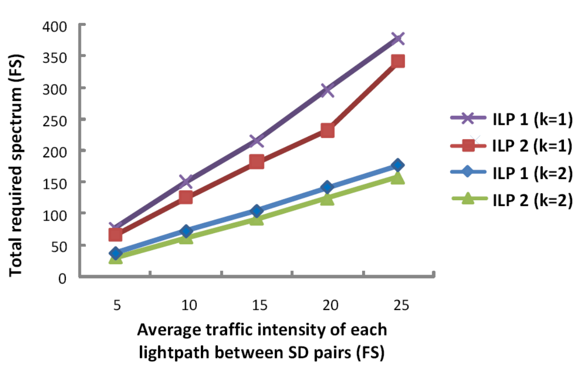

Figure 3: Total required spectra versus traffic demand intensities per node pair (COST 239).

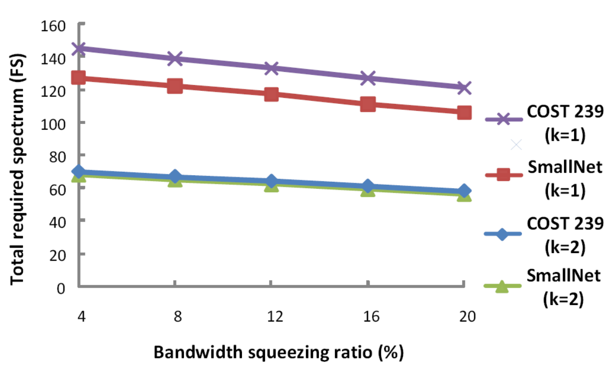

Figure 4: Total required spectra versus maximal bandwidth squeezing ratios.

assignment without fixed channel center frequency allows for different center frequency for each lightpath in different time slots, while the case with fixed channel center frequency requires each lightpath to use the same center frequency at any time slot. We also evaluate the impact of the number of routes for selection on the design performance. It is reasonable to see that the case of two routes (i.e., $k = 2$) requires a smaller number of FSs compared to the case of a single route (i.e., $k = 1$) since the former has more flexibility in route selection. Considering bandwidth squeezing, Fig. 4 shows the results of the optimal spectrum assignment under different bandwidth squeezing ratios. We have only considered the case *with* fixed channel center frequency though similar results can be obtained for the case *without* fixed channel center frequency. In Fig. 4, it is reasonable to see that with an increasing bandwidth squeezing ratio, the required spectrum decreases since a larger bandwidth squeezing ratio corresponds to more spectrum overlap between two neighboring optical channels.

5. CONCLUSION

We took advantage of flexible bandwidth and spectrum allocation of the elastic optical networks to handle time-dependent traffic demands so as to achieve the best spectrum sharing. In [4], we have evaluated the performance of time-dependent spectrum allocation for the case of a single link which has now been extended to the general mesh-network in this paper. To achieve the best optical spectrum sharing, we developed two ILP optimization models *with* and *without* fixed channel center frequency. Simulation results were reported under different combinations of experimental parameters.

ACKNOWLEDGMENT

This work was jointly supported by the National 863 Plans Project of China (2012AA011302), National Natural Science Foundation of China (NSFC) (61172057, 61322109), and Natural Science Foundation of Jiangsu Province (BK2012179, BK20130003).

REFERENCES

1. ITU-T Recommendation G694.1, "Spectral grids for WDM applications: DWDM frequency grid," v2.0, 2012.
2. Zhang, G., et al., "A survey on OFDM-based elastic core optical networking," *IEEE Commun. Surv. Tut.*, Vol. 15, No. 1, 65–87, 2013.
3. Shen, G., et al., "Maximizing time-dependent spectrum sharing between neighboring channels in CO-OFDM optical networks," *Proc. ICTON*, 2011.
4. Zhao, X., et al., "Optimal time-dependent spectrum sharing between neighboring elastic optical channels over a single link," *Proc. ACP*, 2013.
5. Klinkowski, M., et al., "Elastic spectrum allocation for time-varying traffic in flexgrid optical networks," *IEEE J. Sel. Areas Commun.*, Vol. 31, No. 1, 26–38, Jan. 2013.
6. Sone, Y., et al., "Bandwidth squeezed restoration in spectrum-sliced elastic optical path networks (SLICE)," *J. Opt. Commun. Netw.*, Vol. 3, No. 3, 223–233, Mar. 2011.