ILP models for the problem of routing and spectrum allocation in EONs

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1. Introduction

In recent years, with the development of new technologies such as high-definition video, cloud computing, and IoT (Internet of Things), the amount of network traffic around the world has been increasing rapidly. The growth in traffic has driven continuous innovation in the architecture and technology of optical networks. In 2009, Jinno et al. [1] proposed a so-called SLICE architecture, driving the evolution in optical network architectures from fixed grid wavelength division multiplexing (WDM) -based networks which are the so-called wavelength switched optical networks (WSONs) to the flexible grid elastic optical networks (EONs). By using a flexible wavelength allocation technique with smaller and more flexible granularity of spectrum which is called frequency slot (FS), EONs can improve the efficiency and flexibility for diverse traffic transmission.

However, due to the small granularity in EONs, the resource allocation problems become more complicated than that of the existing WSONs. For instance, EONs impose more restrictions on the establishment of light paths, that is, the FS allocated to a light path must be contiguous in the spectral domain. Such a problem is the well-known routing and spectrum allocation (RSA) problem, which has been proved as NP-hard by Ref. [2].

2. ILP models for RSA problem

Our work systematically summarizes the integer linear programming (ILP) models for the RSA problem in existing works from two aspects: routing and spectrum allocation. With respect to routing, there are Path-type and Node-type models. With respect to spectrum allocation, Slot-type and Channel-type models. By combining the routing models and spectrum allocation models, the ILP models of the RSA problem can be divided into four types: Path/Slot, Path/Channel, Node/Slot, and Node/Channel.

2.1 Path/Slot model

Path/Slot model is a model that transmission paths are selected from the prepared candidate paths and that allocates FSs by using variables corresponding to themselves. The following eqs. (1) to (3) are its typical formulations. Among them, R is the set of connection requests, and P_r is the set of candidate paths for serving connection request $r \in R$. n_r^p is a set of constants that indicate the number of FSs required for transmitting connection request r by using candidate path p. x_r^p and $o_{rr'}$ are binary variables, that indicate whether connection request r uses path p, and the order of the FSs used in spectrum by connection request r and r', respectively. f_r is a nonnegative integer variable that indicates the index of the first FS used by connection request r.

$$\sum_{p \in P_r} x_r^p = 1, \quad \forall r \in R \tag{1}$$

$$o_{rr'} + o_{r'r} = 1, \quad \forall r, r' \in R : r \neq r' \tag{2}$$

$$\begin{gathered} f_r + n_r^p \leq f_{r'} + M\left[3 - \left(x_r^p + x_{r'}^{p'} + o_{rr'}\right)\right], \\ \forall r, r' \in R, p \in P_r, p' \in P_{r'} : r \neq r', p \cap p' \neq \emptyset \end{gathered} \tag{3}$$

Eq. (1) indicates that only one path p can be selected for any connection request r from the set of candidate paths. Eqs. (2) and (3) together suggest the spectrum non-overlapping constraints between different connection requests for Path-type models.

2.2 Path/Channel model

Path/Channel model is a model that transmission paths are selected from the prepared candidate paths and that allocates FSs by using variables corresponding to the prepared candidate channels which consist of multiple adjacent FSs. The formulation of routing constraint for Path/Channel model is similar to that for Path/Slot model. And the formulation of spectrum non-overlapping constraint for it are shown as eq. (4).

$$\sum_{r\in R}\sum_{\substack{p\in P_r\\ e\subseteq p}}\sum_{c\in C_r^p}\delta_r^{pcf}x_r^{pc}\leq 1,\quad \forall e\in E, f\in F \tag{4}$$

In eq. (4), E, F and C_r^p are the sets of links in network topology, FSs on each link, and candidate channels that fit the number of required FSs for transmitting connection request r by path p, respectively. δ_r^{pcf} is a binary constant that indicates whether channel c containing the FS f is assigned to connection request r on path p. x_r^{pc} is a binary variable, that indicates whether connection request r uses channel c on path p.

2.3 Node/Slot model

Node-type models construct transmission paths for given connection requests by using variables corresponding to links as shown in eq. (5). V, σ_v^+, σ_v^- are the sets of nodes in network topology, links leaving from node v, and links entering node v, respectively. s_r and d_r indicate the index of origin and destination nodes for connection request r, respectively. And x_r^e is a binary variable, that denotes whether connection request r uses link e. Eq. (5) using flow conservation law indicates that at each node in the network, one connection request can use only one path.

$$\sum_{e\in\sigma_v^+}x_r^e-\sum_{e\in\sigma_v^-}x_r^e=\begin{cases}1 & if\ v=s_r\\ -1 & if\ v=d_r\\ 0 & otherwise\end{cases} \tag{5}$$
$$\forall v\in V, r\in R$$

Node/Slot model is a Node-type model that allocates FSs with the formulation similar to that of the Path/Slot model.

2.4 Node/Channel model

Node/Channel model is a Node-type model that constructs transmission paths with the formulation similar to that of Node/Slot model and allocates FSs employing a formulation similar to that of the Path/Channel model.

3. Simulation and numerical results

We set the objective functions of all four models to minimize the maximum index of the FSs used, and perform a comparative simulation experiment to compare between the models on the N6S9 network which is consisting of 6 nodes and 18 directed links. Table 1 shows the average of the results of 20 traffic data sets when the number of connection requests is 40. The channels used in the model for both Channel-types (i.e., Path/Channel and Node/Channel) contain all cases of channels that can be used in the entire spectrum. "K" is the number of candidate paths. "FS index" is the value of objective at optimal solution.

We can observe that the Path/Channel model showed overwhelming performance. Considering the advantages of the model, the availability of the Path/Channel model in large backbone networks (e.g., NSFNET and ARPANET) and more complex EONs (e.g., space-division multiplexing elastic optical networks) are also worth being looked forward to.

References

[1] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone and S. Matsuoka, "Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies," IEEE Communications Magazine, vol. 47, no. 11, pp. 66~73, 2009.

[2] Y. Wang, X. Cao and Y. Pan, "A study of the routing and spectrum allocation in spectrum-sliced elastic optical path networks," 2011 Proceedings IEEE Infocom, pp. 1503~1511, 2011.

Table 1: Results of comparative experiment at $|R|=40$ on N6S9 network

	Path/Slot			Path/Channel			Node/Slot	Node/Channel
	K=2	K=3	K=4	K=2	K=3	K=4		
FS index	28.05	27.50	27.50	28.05	27.50	27.50	27.50	27.50
Runtime (s)	0.38	14.73	4.69	0.19	0.23	0.29	199.37	441.41