# Efficient Routing and Spectrum Allocation Considering QoT in Elastic Optical Networks

Bingbing Li and Young-Chon Kim

***Abstract*—In recent years, OFDM-based elastic optical network (EON) has drawn a lot of attention in both academia and industry. Compared to traditional optical wavelength division multiplexing (WDM) network, EON is capable of supporting variable data rate, accommodating traffic demands flexibly, and utilizing spectrum more efficiently. Accordingly, the resource management in EON is different from that in WDM networks and addresses new challenges in network design and control. In this paper, we study the routing and spectrum allocation (RSA) problem in EON. We propose an efficient link-based mixed integer linear programming (MILP) model with the objective to optimally utilize the spectrum resources while considering the Quality of Transmission (QoT). Then the performance of the proposed model is examined through a case study.**

***Keywords*—Elastic optical network, link-based model, MILP, RMLSA, QoT.**

## I. Introduction

WITH the exponential growth of end users and the emergence of bandwidth intensive applications, Internet traffic has been increasing sharply during last decades. The compound annual growth rate (CAGR) of IP traffic in backbone networks is estimated to be kept at 24~53% in the near future [1]. To meet the demand, optical Wavelength Division Multiplexing (WDM) network has been widely deployed for Internet backbone and the service providers keep on enlarging network capacity and expanding network size. The bandwidth of one wavelength has been continuously improved to 10 Gbps, 40 Gbps, and nowadays, 100 Gbps. However, traditional WDM networks adopt the ITU-T fixed-grid standard which divides the spectrum of C-band into fixed 50 GHz frequency slots (FSs) [2]. Data rate of 400 Gbps or higher for one wavelength channel cannot be achieved by the fixed grid and modulation format based on existing standard. On the other hand, the bandwidth demands among various applications show high heterogeneity. Current optical network operating on the fixed grid has to allocate a complete wavelength even when required bandwidth is much smaller than the wavelength capacity, leading to inefficient usage of spectrum resources. The support for 400 Gbps, 1 Tbps, and other high bit rate demands and the flexibility to accommodate heterogeneous demands drive us to develop a new paradigm which can overcome the shortages of WDM networks.

Manuscript received February 28, 2015. This work was supported by Basic Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2014-055177).

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Recently, the Elastic Optical Network (EON) has been proposed. The main advantages of EON are: (1) bandwidth allocation based on finer granularity of a subcarrier rather than a wavelength; (2) ability to dynamically adapt channel date rate to required demand via bandwidth-variable transceivers (BVT) and bandwidth-variable optical crossconnect (BV-OXC); (3) high spectrum efficiency by flexibly adjusting modulation format via software. Among all enabling technology to realize EON architecture, optical Orthogonal Frequency Division Multiplexing (OFDM) has become the focus of extensive research effort. OFDM is a multi-carrier modulation technique by which the data flow is distributed over an arbitrary set of orthogonal low data rate subcarriers. These orthogonal subcarriers overlap in the frequency domain, leading to flexible resource allocation and efficient utilization of the spectrum resources. Comparing to traditional WDM networks, OFDM-based EON can achieve sub-wavelength and super-wavelength accommodation for various traffic demands. By allocating one or multiple contiguous FSs with appropriate modulation format, a spectrum path can be all-optically established between the source and destination nodes. If two spectrum paths share one or more common physical links, these spectrum paths should be separated by guard band (GB) for filtering and recovering signal. As the fundamental issue in EON, the Routing and Spectrum Allocation (RSA) problem should be taken into account, which is different from and more complex than the traditional Routing and Wavelength Assignment (RWA) problem in WDM networks.

In OFDM-based EON, each subcarrier can be processed individually through digital signal processing (DSP) implemented at both the transmitting and the receiving ends. That is, the modulation format can be adjusted according to the traffic demand and the transmission distance of optical path. Due to the accumulated signal impairment on the consecutive fiber links along the optical path, the maximum optical transmission distance (called transmission reach) is severely limited when the quality of transmission (QoT) is considered. Although optical OFDM can support significant higher channel capacity, the choice of the modulation format has to take into account the QoT. The relationship between the capacity and transmission reach is given in [3]: an extra bit can be added per symbol, and the transmission reach should be halved for every 3 dB gain in signal-to-noise ratio (SNR). For example, modulation format 8QAM (3 bit/symbol) can be used instead of QPSK (2 bit/symbol), while the transmission reach of 8QAM signal should be reduced to half the transmission reach of QPSK. The consideration of QoT poses additional challenges on RSA: decision of appropriate modulation level.

To address all the issues mentioned above, new strategies and algorithms for Routing, Modulation Level and Spectrum Allocation (RMLSA), have to be developed. The challenges in new spectrum management schemes are:

- *Spectrum contiguity constraint*: The spectrum allocated to a request must be a block of contiguous FSs.
- *Spectrum continuity constraint*: This constraint is similar to the wavelength continuity constraint in WDM networks. The same contiguous FSs must be allocated on the consecutive links along the optical end-to-end path of a request.
- *Decision of modulation level*: The choice of modulation level is affected by required bandwidth and the limitation on transmission reach.

The RMLSA problem has been studied in several literatures. A *path-based* ILP model was presented in [4] to solve static RMLSA problem. In the model, $k$ ($k$ = 3) candidate paths for each source-destination pair are pre-computed. The demand can only be routed on one of these $k$ paths. The objective is to minimize the maximum utilized spectrum on any link in the network with considering the spectrum contiguity and non-overlapping constraint. Reference [5] proposed a different, *link-based* ILP model for RSA with the objective to minimize the maximal index of used FSs in the entire network. To reduce the number of variables and computational complexity, the model adopted the method in [4] to define each spectrum path by using the starting and ending FS indexes. Another *link-based* ILP model of RSA has been studied in [6]. This work considered two objectives to minimize: the maximum subcarrier index allocated on any fiber, and the total number of subcarriers over all fibers. Both [5] and [6] assumed the traffic demand in unit of FS, and the issue of ML decision was not considered. The model in [4] addressed the decision of modulation level. The flexibility is considerably limited due to the essence of path-based model. Once the $k$ shortest paths are computed, the modulation level of a path is determined.

In this paper, we study the RSA problem in transparent EON. An efficient link-based MILP formulation is proposed to determine the routing, modulation level and spectrum allocation to each traffic demand with the consideration of QoT. To improve the spectrum efficiency, it tends to choose highest modulation level. However, the transmission reach of the optical path with the highest modulation level is very limited if acceptable QoT is considered. Hence, the proposed model needs to find the tradeoff among the number of required FSs, modulation level, and transmission reach. Our objective is to minimize the number of required FSs in network to accommodate all traffic demands.

The rest of this paper is organized as follows: In section II, the mathematical model is presented and explained. In section III, the MILP models are evaluated and compared by illustrative examples; and the numerical results will be analyzed. Finally, we conclude the paper in Section IV.

## II. Mathematical Formulation

The physical topology of network is represented as $G(V, E)$, in which $V$ is the set of nodes and $E$ is the set of links. Given the physical topology, the traffic matrix, and the limit of transmission reach for various modulation formats as the input, we need to:

- provision all ($s$, $d$) pairs: determine the route, ML and SA for each traffic demand

- optimize the spectrum utilization: minimize the sum of the maximum FS index over all fibers in network

The following assumptions are stated in the RMLSA model: (a) The fiber capacity in terms of FSs is not limited on all links; (b) Connection requests are unidirectional, and an end-to-end all-optical path must be found for each request; (c) No specific path for a connection is given in advance, i.e., any possible path and any possible set of contiguous FSs will be evaluated while solving the model.

The notations and formulation are summarized as follows:

**Indexing rules:**

($s$, $d$)- source-destination pair, $s$ and $d$ index the originating and terminating nodes of a connection

($m$, $n$)- node pair, represent a fiber link in physical topology

**Given:**

$G(V,E)$- Network physical topology consisting of node set $V$ and edge set $E$

$TM = [\lambda^{sd}]$ - Traffic matrix, $\lambda^{sd}$- traffic demand from $s$ to $d$, $s,d \in V$

**Parameters:**

$C$ - Base capacity of a FS with single bit per symbol modulation (BPSK)

$R$ - Set of modulation levels, $R = \{1, 2, 3, ...\}$, $r \in R$

$L_{mn}$- Length of physical link ($m$, $n$)

$L_r$ - Maximum optical transmission reach of a lightpath adopting modulation level $r$

$GB$- Number of FSs for one filter guard band

**Variables:**

$N_{sd,r}$ - (integer) Number of FSs allocated to serve request ($s$, $d$) with modulation level $r$

$NFS_{sd}$ - (integer) Number of FSs allocated to serve request ($s$, $d$)

$Nl_{mn}^{sd,r}$ - (integer) Number of FSs allocated to serve request ($s$, $d$) with modulation level $r$ on physical link ($m$, $n$)

$S_{sd}$ - (integer) Index of the starting FS allocated to serve request ($s$, $d$)

$E_{sd}$ - (integer) Index of the ending FS allocated to serve request ($s$, $d$)

$X_{s'd'}^{sd}$ - (binary)

$X_{s'd'}^{sd} = 1$, if $S_{sd} > E_{s'd'}$

$X_{s'd'}^{sd} = 0$, if $S_{s'd'} > E_{sd}$

$Y_{mn}^{sd,r}$ - (binary)

$Y_{mn}^{sd,r} = 1$, if request ($s$, $d$) using modulation level $r$ is routed on physical link ($m$, $n$)

$Y_{mn}^{sd,r} = 0$, otherwise

$Z_{sd,r}$ - (binary)

$Z_{sd,r} = 1$, if modulation level $r$ is determined for ($s$, $d$)

$Z_{sd,r} = 0$, otherwise

$MI_{mn}$ - (integer) Maximum index of FS allocated on link ($m$, $n$)

**Objective function:**

$$Minimize \sum_{(m,n)\in E} MI_{mn}$$

subject to the following constraints:

1) *Single path routing constraint*:

$$\sum_{n\in V} Y_{mn}^{sd,r} - \sum_{n\in V} Y_{nm}^{sd,r} = \begin{cases} 1, \text{ if } m=s \\ -1, \text{ if } m=d \\ 0, \text{ otherwise} \end{cases} \quad \forall (s,d), m\in V, \forall r\in R \tag{1}$$

Constraint (1) limits that for each request (*s*, *d*), only one path can be followed and the traffic demand cannot be split.

2) *Flow conservation constraint*:

$$\sum_{n\in V} Nl_{mn}^{sd,r} - \sum_{n\in V} Nl_{nm}^{sd,r} = \begin{cases} N_{sd,r}, \text{ if } m=s \\ -N_{sd,r}, \text{ if } m=d \\ 0, \text{ otherwise} \end{cases} \quad \forall (s,d), m\in V \tag{2}$$

Constraint (2) ensures the flow conservation in terms of number of FSs for any (*s*, *d*) pair.

3) *Starting Frequencies ordering constraint*:

$$X_{s'd'}^{sd} + X_{sd}^{s'd'} = 1 \tag{3}$$

Constraint (3) ensures that either the starting FS of (*s*, *d*) is smaller than ending FS of (*s'*, *d'*), or the starting FS of (*s'*, *d'*) is smaller than ending FS of (*s*, *d*).

4) *Spectrum continuity and non-overlapping spectrum allocation constraints*:

$$E_{s'd'} - S_{sd} \le F \times (X_{s'd'}^{sd} + 2 - Y_{mn}^{sd,r} - Y_{mn}^{s'd',r'}) - GB - 1, \quad \forall (s,d),(s',d'): sd \ne s'd', \forall (m,n)\in E \tag{4}$$

Constraint (3) and (4) ensure that when two spectrum paths share common link(s) they must not overlap in frequency domain. In detail, when two spectrum paths share a common link (*m*, *n*) ($Y_{mn}^{sd,r} = Y_{mn}^{s'd',r'} = 1$) and $S_{s'd'} > E_{sd}$ ($X_{s'd'}^{sd} = 0$), we can obtain $E_{s'd'} + GB + 1 \le S_{sd}$, which satisfies the non-overlapping requirement; otherwise, constraint (4) always holds.

5) *Physical Link Usage Constraint*:

$$Nl_{mn}^{sd,r} \le Y_{mn}^{sd,r} \cdot F, \quad \forall (s,d), \forall (m,n)\in E, \forall r\in R \tag{5}$$

Constraint (5) ensures that only the FSs on those links (*m*, *n*) which are used to route request (*s*, *d*) can be allocated.

6) *Spectrum path MF constraint*:

$$N_{sd,r} \le Z_{sd,r} \cdot F, \quad \forall (s,d), \forall r\in R \tag{6}$$

Constraint (6) determines which of the modulation level is used for the spectrum path between (*s*, *d*) pair.

7) *Modulation Format Constraint*:

$$\sum_{r\in R} Z_{sd,r} = 1, \quad \forall (s,d) \tag{7}$$

Constraint (7) asserts that each spectrum path can adopt only one modulation format.

8) *Transmission reach constraint*:

$$\sum_{(m,n)\in E} Y_{mn}^{sd,r} \cdot L_{mn} \le L_r, \quad \forall (s,d), \forall r\in R \tag{8}$$

Constraint (8) ensures that the path length of any request (*s*, *d*) adopting modulation level *r* cannot greater than the maximum optical transmission reach under *r*.

9) *Max_FS_ID Constraint*:

$$MI_{mn} \ge E_{sd} - F \cdot (1 - Y_{mn}^{sd,r}), \forall (s,d), \forall (m,n)\in E, \forall r\in R \tag{9}$$

Constraint (9) ensures that $MI_{mn}$ is greater than the ending FS of any request (*s*, *d*) which is routed on link (*m*, *n*).

10) *Others:*

Calculation of the number of FSs for each (*s*, *d*) with modulation level *r*:

$$N_{sd,r} = Z_{sd,r} \times \left\lceil \lambda_{sd} / r\cdot C \right\rceil, \forall (s,d), \forall r\in R \tag{10}$$

Calculation of $E_{sd}$:

$$E_{sd} = S_{sd} + NFS_{sd} - 1, \forall (s,d) \tag{11}$$

Calculation of $NFS_{sd}$:

$$NFS_{sd} = \sum_{r\in R} N_{sd,r}, \quad \forall (s,d) \tag{12}$$

## III. Numerical Results

The numerical results will be shown and analyzed in this section. To evaluate the performance of the proposed model, we apply it to a case study. Our results are obtained via optimization software IBM ILOG CPLEX Optimization Studio Version12.6 on the computer with Intel Core (TM) i5-2500 CPU (3.30 GHz) and 8 GB RAM.

The case study is implemented on a four-node ring network with all link distances of 500km (shown as Fig. 1). Nodes are connected by bi-directional links, one fiber on each direction. The filter guard band is 2 FSs. The traffic demands for each source-destination pair is randomly generated between 1 and *D* Gbps (*D* = 100, 150, 200, 250, 300, 400). We assume the spectral width of a FS is 12.5 GHz. Three modulation formats are considered: BPSK, QPSK and 8QAM. The parameters for different modulation formats are summarized in Table I.

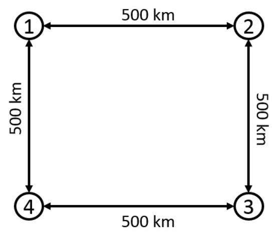


Fig. 1. Four-node network topology.

TABLE I
Parameters for Different Modulation Format

| Modulation Format | Spectrum Efficiency (bps/Hz) | Data Rate per Subcarrier (Gbps) | Transmission Reach (km) |
|---|---|---|---|
| BPSK | 1 | 12.5 | 2000 |
| QPSK | 2 | 25 | 1000 |
| 8QAM | 3 | 37.5 | 500 |

Fig. 2. shows the number of required FSs to accommodate all traffic in network according to different values of *D* (large value of *D* represents heavy traffic load). As a reference, we evaluate the scenario that only the modulation format BPSK is

supported to quantify the spectrum usage affected by flexible choice of multiple modulation levels. The group of orange bars indicates the results for the case with multiple modulation formats, shorted as "Multi-MF". The group of blue bars indicates the results for the case with single modulation format, shorted as "BPSK". Obviously, the number of required FSs of Multi-MF is much less than that of BPSK under all different *D*. Multi-MF can achieve 45-53% saving on spectrum usage in terms of required FSs, comparing to the BPSK case. In addition, the saving on spectrum resources is improved with increasing network traffic load. These observations indicate that to accommodate the same network load, Multi-MF can outperform BPSK by efficiently allocating spectrum resources while satisfying the requirement of QoT.

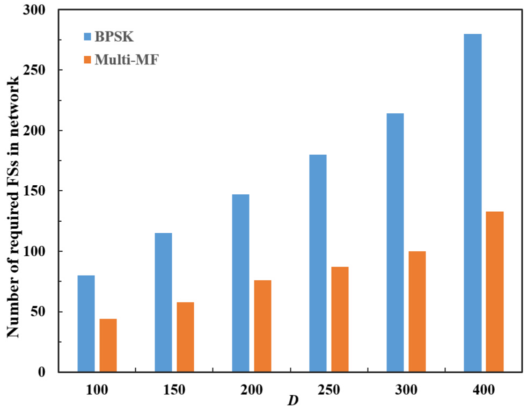


Fig. 2. Number of required FSs in network according to different *D*.

TABLE II
MAXIMUM INDEX OF FS ON LINKS (MULTI-MF)

| Link \ D | 100 | 150 | 200 | 250 | 300 | 400 |
|---|---|---|---|---|---|---|
| 1->2 | 0 | 8 | 5 | 1 | 6 | 19 |
| 1->4 | 9 | 4 | 11 | 18 | 15 | 8 |
| 2->1 | 6 | 6 | 18 | 21 | 14 | 14 |
| 2->3 | 1 | 9 | 6 | 2 | 8 | 22 |
| 3->2 | 8 | 9 | 22 | 25 | 19 | 21 |
| 3->4 | 6 | 10 | 3 | 3 | 14 | 24 |
| 4->3 | 9 | 4 | 11 | 17 | 14 | 8 |
| 4->1 | 5 | 8 | 0 | 0 | 10 | 17 |

TABLE III
MAXIMUM INDEX OF FS ON LINKS (BPSK)

| Link \ D | 100 | 150 | 200 | 250 | 300 | 400 |
|---|---|---|---|---|---|---|
| 1->2 | 1 | 15 | 9 | 24 | 13 | 17 |
| 1->4 | 15 | 8 | 21 | 11 | 31 | 40 |
| 2->1 | 18 | 11 | 19 | 18 | 28 | 37 |
| 2->3 | 3 | 19 | 12 | 30 | 18 | 23 |
| 3->2 | 24 | 20 | 30 | 32 | 44 | 57 |
| 3->4 | 4 | 21 | 22 | 33 | 32 | 43 |
| 4->3 | 15 | 8 | 20 | 11 | 29 | 37 |
| 4->1 | 0 | 13 | 14 | 21 | 19 | 26 |

Table II and III show the maximum index of FS on all links based on Multi-MF and BPSK, respectively. It can be found that the difference among the maximum FS indexes of links is larger based on BPSK than that based on Multi-MF. For example, when *D* = 100, the difference is 9 FSs between the links with the smallest and the largest indexes under Multi-MF while the difference increases to 23 FSs under BPSK. Because the number of required FSs is determined solely on the bandwidth of request in the single MF scenario, the benefit of high spectral efficiency from OFDM cannot be exploited. Again, this difference becomes larger according to increasing the traffic load.

## IV. CONCLUSION

In recent years, OFDM-based EON has been extensively studied as a promising paradigm which has high flexibility in traffic accommodation and can improve spectrum utilization. We have developed an MILP model that addresses the essential RMLSA issue in EON, focusing on determining appropriate modulation format for each request with the consideration of QoT. The numerical results showed that the proposed model could reduce the number of FSs required to accommodate all traffic in network, comparing to the scheme which assumed a fixed modulation format. Moreover, multiple modulation formats helps alleviate the uneven consumption of spectrum among fiber links.

Since the computational complexity of optimization model is too high, we consider developing heuristic algorithms to solve the RSA problem in large-size networks for future work. In addition, the energy efficiency in EON can be studied.

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