Energy Efficient Spectrum Allocation in IP-over-EON with Traffic Grooming

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Abstract. Elastic optical network (EON) based on flexible grid and optical orthogonal frequency division modulation (OFDM) has emerged as an innovative approach to meet the ever-increasing demand. In EON, traffic grooming can improve the efficiency of spectrum by removing the guard band between two adjacent channels. Although network spectrum resource can be utilized more efficiently by traffic grooming, the operation leads to considerable power consumption due to the high data rate of transponder and electronic processing overhead at intermediate nodes. In this paper, we investigate the power consumption of IP-over-EON with traffic grooming. An efficient mixed integer linear programming (MILP) model is proposed to solve the spectrum allocation problem with the objective to minimize network power consumption in IP-over-EON with traffic grooming. The performance of the proposed model is evaluated in terms of spectrum allocation and energy consumption through a case study.

Keywords: Elastic Optical Network · MILP · Power consumption · Traffic grooming

1 Introduction

In recent years, the Elastic Optical Network (EON) has drawn a lot of attention as an innovative approach to utilize spectrum resource efficiently and flexibly. The widely-deployed Wavelength Division Multiplexing (WDM) networks adopt the ITU-T fixed-grid standard which divides the spectrum range of 1530-1565 nm (C-band) into fixed 50 GHz frequency slots (FSs). 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. Comparing to traditional WDM networks, OFDM-based EON can achieve sub-wavelength and super-wavelength accommodation for various traffic demand. By allocating enough bandwidth with appropriate modulation format, a spectrum path can be all-optically established between source and destination nodes. If two spectrum paths share one or more common physical links, these spectrum paths should be separated by guard band for filtering and recovering signal.

Traffic grooming is a technique to aggregate multiple low-data-rate traffic requests and groom them onto a high-speed wavelength channel in traditional WDM networks to improve wavelength utilization. In the context of EON, traffic grooming can be realized in either electrical layer or optical layer. Electrical traffic grooming follows the

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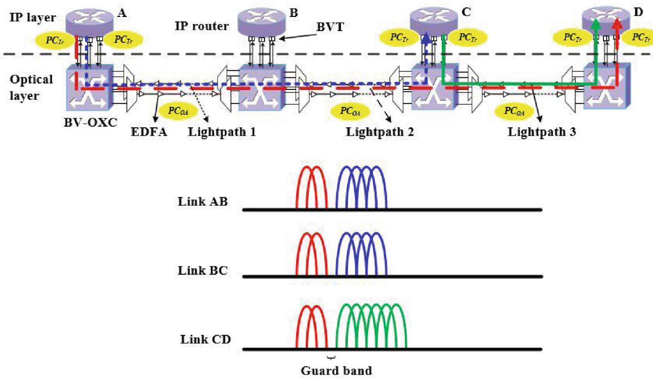
same way with that in WDM networks, introducing additional electrical switching and optical-electrical-optical (OEO) conversion. Although lots of research work has been performed in traditional IP-over-WDM networks [1–6], there is little attention on the traffic grooming issue in EON. In EON, Bandwidth Variable Transponder (BVT) can support much larger capacity, 400 Gbps or beyond, compared to the transponder in WDM networks. This makes traffic grooming in EON obviously important. Reference [7] introduces the traffic grooming in EON for the first time and presents two MILP models based on with and without traffic grooming, both with the objective to minimize the average spectrum utilization. In the objective function, average spectrum utilization is a weighted value in terms of fiber lengths in network topology. The link-based models are based on "gridless" EON and electrical traffic grooming in order to reduce guard band overhead. Another MILP model related to electrical traffic grooming in IP-over-EON is proposed by [8]. In this model, k-shortest paths are pre-computed for each (s, d) pair. Different from [7], this work is based on the mini-grid scenario and considers allocating FSs to each traffic demand. In addition, the capacity of an optical fiber in terms of FSs, and the number of BVTs at each node are limited. With limited resources (spectrum, transponders), the objective is to maximize total amount of served traffic demand. The spectrum continuity and contiguity constraints and non-overlapping constraint are ensured. Reference [9] proposes an MILP model to design the spectrum sliced elastic optical path networks under traffic grooming. It extends the work in [7] by adding the constraint on total number of transceivers. The objective function is the same with that in [7]: to minimize the average spectrum utilization in network. But this work aims to efficiently utilize resources in terms of both transceivers and spectrum.

Although the original intention of traffic grooming in IP-over-EON was to improve spectrum utilization and reduce required BVTs, huge power consumption caused by traffic grooming is an unavoidable problem. Existing optimization models for IP-over-EON with traffic grooming aim to minimizing the average spectrum utilization [7], or maximizing the amount of served traffic demand under limited spectrum resource on each fiber link [8], while no or little attention has been paid to the power consumed by traffic grooming. In this paper, we study the bandwidth allocation in IP-over-EON with traffic grooming. A link-based MILP formulation is proposed to determine the routing and bandwidth allocation to each traffic demand. Different from existing models, our objective is to minimize the network power consumption to accommodate all traffic demands.

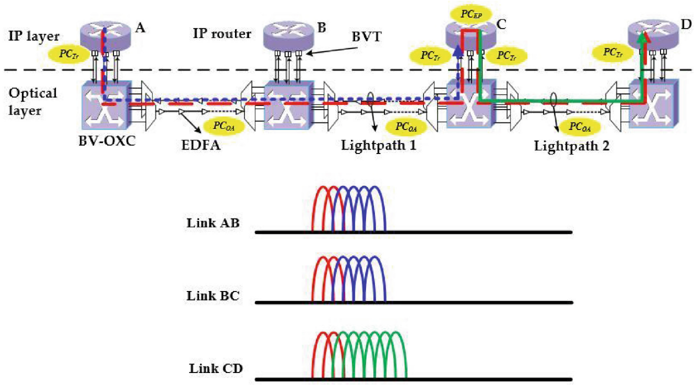
The rest of this paper is organized as follows: In Sect. 2, the network architecture and power consumption model are analyzed. The mathematical model is presented and explained in Sect. 3. In Sect. 4 the MILP model is evaluated and compared with traditional model by case study; and the numerical results will be analyzed. Finally, we conclude the paper in Sect. 5.

2 Problem Statement

The network models of an EON without and with traffic grooming are illustrated in Fig. 1. IP-over-EON consists of two layers: IP layer and optical layer. IP routers are deployed at network nodes and constitute the IP layer (electrical layer). Network traffic is aggregated into IP router from low-end routers in access networks. The functions of IP router is to generate (as a source node), process (as a grooming node) and drop (as a destination node) IP traffic. They are connected with Bandwidth Variable Optical Cross-Connect (BV-OXC) via BVTs, which are used to emit and terminate lightpaths. With the OEO processing capability of transponder, full wavelength conversion can be realized at switch node. Two adjacent BV-OXCs are interconnected by an optical fiber link and responsible for switching lightpaths optically. All the BV-OXCs and optical fibers construct the optical layer. For the long-distance transmission of optical signals, erbium doped fiber amplifiers (EDFA) are deployed on optical fibers. Without traffic grooming, an end-to-end all-optical lightpath is established for each connection request between source and destination node pair. The establishment of one lightpath needs a pair of BVTs. As shown in Fig. 1(a), three connection requests (A-C, C-D, A-D) consume six



(a) IP-over-EON without traffic grooming



(b) IP-over-EON with traffic grooming

Fig. 1. Network architecture and spectrum allocation

BVTs to establish three lightpaths, each dedicated for a source-destination pair. If the demand for each request is low, the utilization of BVT is considerably low, compared with the allowable capacity of BVT. On the contrary, traffic grooming enables that multiple traffic flows can be groomed onto high-speed channel and transmitted together. As shown in Fig. 1(b), only two lightpaths (A-C, C-D) are established to serve three connection requests. IP traffic flow A-D can be consecutively carried by lightpaths A-C and C-D, resulting in saving of two BVTs. Moreover, the spectrum for guard band which is necessary to separate two lightpaths on their common links can be saved.

Based on the direct bypass IP-over-EON shown as Fig. 1(a), one end-to-end lightpath is established through two BVTs at source and destination nodes of a connection request. There is no electrical processing and the lightpath is switched optically by BV-OXCs at intermediate nodes. The power consumption of BVT (PC_{Tr}) is related to the actual transmission rate (TR). Note that the power consumption for adding/dropping traffic at source/destination nodes is not considered because this power contributor is constant for given traffic matrix. EDFAs are deployed on optical fiber to enlarge optical signal after transmitting certain distance. The power consumed by EDFA is indicated by PC_{OA}. However, the IP-over-EON with traffic grooming introduces additional power consumption for electrical processing at the IP routers of intermediate nodes (PC_{EP}). The request destined to the node (e.g. request A-C) is dropped. And the request which is not destined to the node (request A-D) is groomed with a locally added request (request C-D). The power consumption by grooming operation depends on the amount of traffic processed in IP routers.

3 Mathematical Formulation

Based on the networks architecture and power consumption model introduced in previous section, the MILP optimization model is presented and explained in this section. The physical topology of network is represented as a graph G (V, E), in which V is the set of network nodes and E is the set of physical links. Two adjacent network nodes are connected by a pair of physical links, one in each direction. Each link may consist of one or multiple optical fibers. The spectrum resource on optical fiber, the capacity of BVTs and the maximum number of BVTs at each node are assumed to be limited. The traffic matrix is given in advance in which an element indicates the data rate required by each source-destination pair. We need to provision all requests (i.e., determine the route, and bandwidth allocation for each traffic demand) while optimizing the resource utilization (i.e., spectrum, energy etc.). In following part: (s, d) indicates a source-destination pair, s and d index the originating and terminating nodes of a connection request; (i, j) represents a node pair which are the two ends of a virtual link; (m, n) represents a fiber link in physical topology. The notations and parameters are summarized as follows:

Given:
$G(V, E)$- Network physical topology consisting of node set V and edge set E
$TM = [\lambda^{sd}]$- Traffic Matrix, λ^{sd}- Traffic demand from s to d, $s, d \in V$ (in Gbps)
Parameters:
L_{mn}- Length of physical link (m, n) (in Km)
GB- Bandwidth for one filter guard band (in GHz)
C- Total bandwidth of one optical fiber (in GHz)
C_{Tr}- Maximum capacity of an OFDM-transponder (in Gbps)
Max_Tr- Maximum number of transponders at each node
PC_{Tr}- Power consumption of an OFDM-transponder, depending on the TR
PC_{EP}- Power consumption for electrical processing unit amount of traffic (Gbps)
PC_{OA}- Power consumption of an in-line optical amplifier
SP_{total}- Total spectrum allocated for provisioning all traffic demand
PC_{total}- Total power consumption of network

Decision Variables:
$f_{ij,k}^{sd}$- Traffic flow of λ^{sd} that is served by the kth transponder of virtual link (i, j)
N_{ij}- The number of lightpaths between node i and j
$V_{ij,k}$- The bandwidth of an elastic lightpath using the kth transponder on (i, j)
F_{mn}- The number of optical fibres on physical link (m, n)
$PL_{mn}^{ij,k}$- The bandwidth that a lightpath using the kth transponder on virtual link (i, j) uses on physical link (m, n)
$X_{mn}^{ij,k}$- (binary) equals 1 if lightpath using the kth transponder on virtual link (i, j) is routed on physical link (m, n); 0, otherwise
$Y_{ij,k}$- (binary) equals 1 if there is one lightpath using the kth transponder on virtual link (i, j); 0, otherwise

The objective function is to minimize the total power consumption of network to serve all traffic demands:

$$Minimize\ PC_{total}$$

Where

$$PC_{total} = PC_{EP} \times \sum_{i} \sum_{j} \sum_{k} \sum_{s,i \neq s} \sum_{d} f_{ij,k}^{sd} + \sum_{k} \sum_{i} \sum_{j} (V_{ij,k} \times PC_{Tr} + Y_{ij,k} \cdot PC_{Tr}^{0}) + \sum_{(m,n) \in E} A_{mn} \cdot F_{mn} \cdot PC_{OA}$$

The total power consumption of network consists of three parts: power consumption for electrical processing, power consumed by BVTs to establish lightpaths, and power consumed by amplifiers on optical fiber. To compare with traditional model, another objective function is presented to minimize the total allocated spectrum in network to serve all traffic demands:

$$Minimize\ SP_{total}$$

Where

$$SP_{total} = \sum_{(m,n)\in E} \sum_{i} \sum_{j} \sum_{k} (PL_{mn}^{ij,k} + GB \cdot X_{mn}^{ij})$$

Both objective functions are subject to following constraints:

$$\sum_{j} \sum_{k} f_{ij,k}^{sd} - \sum_{j} \sum_{k} f_{ji,k}^{sd} = \begin{cases} \lambda^{sd}, \ if\ i = s \\ -\lambda^{sd}, \ if\ i = d \\ 0, \ otherwise \end{cases} \quad \forall (s,d), \forall i \in V \tag{1}$$

$$\sum_{n} PL_{mn}^{ij,k} - \sum_{n} PL_{nm}^{ij,k} = \begin{cases} V_{ij,k}, \ if\ m = i \\ -V_{ij,k}, \ if\ m = j \\ 0, \ otherwise \end{cases} \quad \forall m, i, j \in V, \forall k \tag{2}$$

$$\sum_{(s,d)} f_{ij,k}^{sd} = V_{ij,k}, \forall i, j \in V, \forall k \tag{3}$$

$$V_{ij,k} \le Y_{ij,k} \cdot C_{Tr}, \forall i, j \in V, \forall k \tag{4}$$

$$\sum_{j} (N_{ij} + N_{ji}) \le Max\_Tr, \forall i \in V \tag{5}$$

$$\sum_{i} \sum_{j} \sum_{k} (PL_{mn}^{ij,k} + GB \cdot X_{mn}^{ij,k}) \le C \cdot F_{mn}, \forall m, n \in V \tag{6}$$

$$\sum_{k} Y_{ij,k} = N_{ij}, \forall i, j \in V \tag{7}$$

$$f_{ij,k}^{sd} \le Y_{ij,k} \cdot \lambda^{sd}, \forall i, j \in V, \forall k \tag{8}$$

$$X_{mn}^{ij,k} \le Y_{ij,k}, \forall i, j, m, n \in V \tag{9}$$

Constraint (1) is the flow conservation constraint for flows of (*s*, *d*) pairs in virtual topology. Constraint (2) is the flow conservation constraint for the routing of lightpaths in optical physical topology. Constraint (3) denotes that the bandwidth of a lightpath is allocated to aggregate sub-flows for all (*s*, *d*) pairs. Constraint (4) limits that: if the *k*th transponder on virtual link is not used ($Y_{ij,k} = 0$), there is no bandwidth allocated; else, the bandwidth allocated for the lightpath on virtual link (*i*, *j*) via the *k*th transponder, cannot be greater than the transponder capacity. Constraint (5) limits the number of lightpaths emitted or terminated on virtual link (*i*, *j*) cannot beyond the maximum number of transponders deployed at each node. Constraint (6) limits that the total allocated bandwidth on physical link (*m*, *n*), including for lightpaths and for guard bands, cannot be greater than the fiber capacity. Constraint (7) calculates the number of lightpaths on virtual link (i, j). Constraint (8) limits that: the amount of flow for (s, d) running on the lightpath, which is established on virtual link (i, j) via the kth transponder, cannot be greater than the demand of request (s, d). Constraint (9) limits that: if there is no lightpath is established by using the kth transponder on virtual link (i, j) ($Y_{ij,k} = 0$), then no lightpath using the kth transponder on virtual link (i, j) is routed on physical link (m, n).

4 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.

4.1 Network Topology and Parameters

The physical topology of the network used in case study is shown as Fig. 2. Adjacent nodes are connected by bi-directional links, one fiber on each direction. The value besides the link indicated physical distance in kilometer. The spectrum resource of each fiber is $C = 1000$ GHz. The filter guard band is $GB = 10$ GHz. The maximum capacity of an OFDM transponder is set to be $C_{Tr} = 400$ Gbps. The maximum number of transponders deployed at each node is $Max\_Tr = 16$. The traffic demands for each source-destination pair is randomly generated between 1 and D Gbps ($D = 100, 200, 300, \ldots, 500$). The modulation format considered is BPSK. The span of optical amplifier is 80 km. The power consumption of network devices considered in our study is summarized in Table 1, referring to some literatures [10, 11].

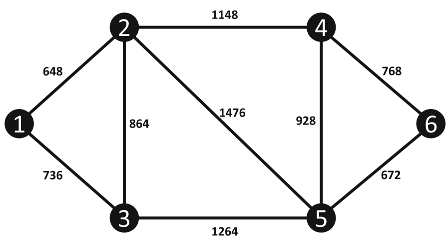


Fig. 2. Network physical topology

Table 1. Power consumption of devices

Devices	Power consumption (Watt)
Transponder	12.5*TR + 31.5
Optical Amplifier	8
Electrical Processing	25 (per Gbps)

4.2 Results and Analysis

Figure 3 presents the total spectrum allocated in network under different traffic load. Comparing to the *Min SP* scheme, *Min PC* model consumes 14.5 % to 93.7 % more spectrum resource according to different traffic load. When traffic load increases, the difference between two schemes becomes smaller. Under low traffic load, *Min PC* scheme tries to put network devices into inactive status to save energy, e.g., some optical fibers can be in sleep mode and the EDFAs on these fibers will not consume any energy. However, keeping less fibers activated means that less choices on routing and spectrum assignment. This may lead to longer routes for connection requests and more spectrums, consequently. While under high traffic load, all optical fibers are activated. The impact of sleep optical fibers on spectrum allocation does not exist. Then *Min PC* scheme can find shorter route and occupy less spectrum.

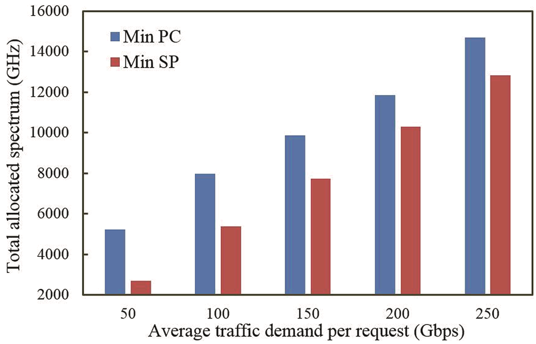


Fig. 3. Total allocated spectrum

The total network power consumption of two models under different traffic load is compared in Fig. 4. It is obvious that *Min PC* shows absolute advantage in term of power consumption. The power consumption of *Min SP* scheme is 6 to 7 times that of *Min PC* under all traffic loads. This is because *Min SP* model essentially aims to minimize

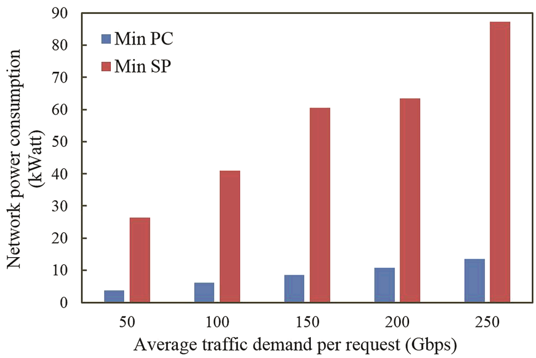


Fig. 4. Network power consumption

spectrum usage, without concerning about the power consumption is a heavy overhead introduced by traffic grooming. To achieve minimal spectrum usage, connection requests are groomed onto a common lightpath, removing the guard bands between adjacent connections and increasing the capacity of lighpath. However, at the same time, the power consumption from BVTs at source and destination nodes and electrical processing at intermediate nodes will be extremely enlarged.

Figure 5 presents the total number of lightpaths established in network under different traffic load. Under low load, *Min PC* needs slightly more lightpaths to support all traffic demand. With the traffic load increasing, the number of lightpaths obtained by *Min PC* becomes less than that by *Min SP*. Two schemes achieve similar performance in view of established lightpaths (i.e., necessary BVTs). Considering the increasing speed and huge amount of Internet traffic, *Min PC* may be more beneficial in future.

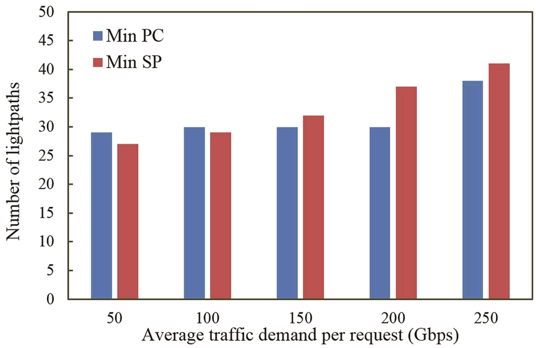


Fig. 5. Number of lightpaths

5 Conclusion

Traffic grooming is an efficient technique to improve the utilization of network spectrum resource in IP-over-EON. However, the grooming operation may introduce considerable power consumption due to the electrical processing in IP layer. In this paper, we investigated the potential to reduce network power consumption in IP-over-EON with traffic grooming. We proposed an MILP model to solve the routing and spectrum allocation problem with the objective to minimize network power consumption. The proposed model was evaluated and compared with traditional model via a case study. The numerical results showed that our proposed model could achieve power saving to a great extent at the cost of slightly more spectrum occupation. And the proposed model also showed advantage in term of BVTs which needed to be deployed in future.

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