Virtual topology design scheme with energy efficiency for IP over elastic optical networks

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The rapid growth of the Internet raises the importance of resource planning of Internet protocol (IP) over elastic optical networks (EONs), which is a challenging task due to more complex and obscure physical constraints of it. Compared with network cost, the power consumption may eventually become the barrier to the expansion of the Internet. We present an energy-efficient virtual topology design (VTD) scheme for IP over EON. We explicitly explain and analyze the mixed integer linear programming model and the heuristic algorithm for this scheme. Numerical results show that the proposed VTD scheme can significantly save power consumption.

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Compared with wavelength division multiplexing (WDM)[1] networks, elastic optical networks (EONs)[2] based on the optical orthogonal frequency division multiplexing (O-OFDM) technique[3] can significantly improve spectrum utilization, while more complex constraints on the routing and spectrum allocation (RSA) problem keep them from being operated in a totally elastic way. There is a new kind of constraint called spectrum continuity constraint (SCC) in RSA problem[4], consisting of two major parts. The first one is almost the same as the conventional weakly connected component (WCC), that is, it must be assigned the same spectrum range on all the physical links (p-links) the optical channel (OC) traverses, which is called spectrum consistency constraint. The second one stemming from EON is called spectrum contiguity constraint, meaning that the frequency units taken by one OC must be contiguous. The latter would cause spectrum fragments and decrease the performance of networks. To surmount this constraint, several solutions, such as split-spectrum approach[5,6], have been studied and proposed.

An alternative solution is the Internet protocol (IP) over EON approach which diverts the problem to flexible IP packet streams[7]. As shown in Fig. 1, the IP over EON is composed of two major layers: the overlay IP (virtual) layer and the underlay optical (physical) layer. In the IP layer, core IP routers with aggregated data traffic are connected to elastic optical switch nodes via fixed line-rate add/drop ports. The optical layer provides OCs with elastic capacity for connections between IP routers. For each OC which may traverse several optical nodes, a pair of elastic transponders is deployed at the two ends for data transmission. Additionally, erbium-doped fiber amplifiers (EDFAs) are deployed on fiber links to regenerate optical signals.

Due to the multi-layer nature of IP over EON, virtual topology design (VTD) is an inevitable and important

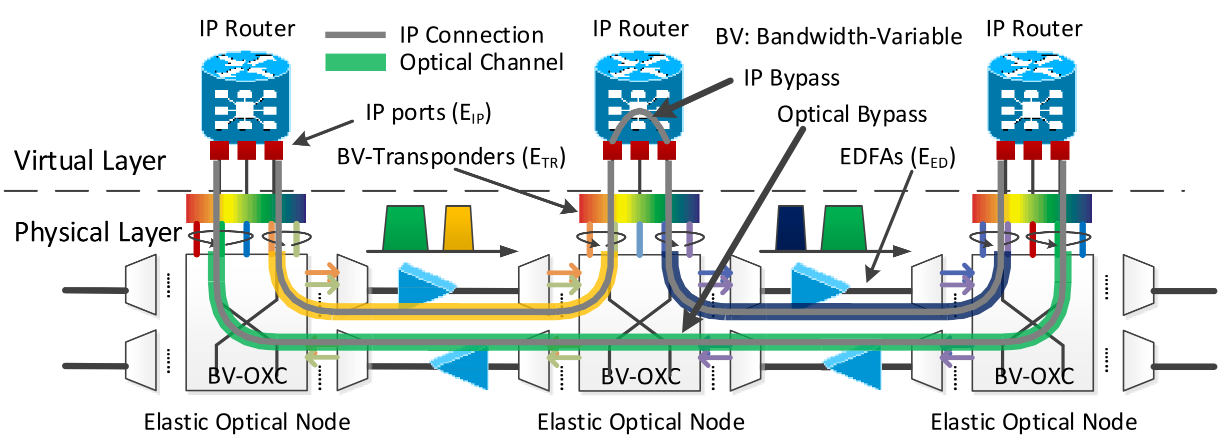

Fig. 1. Architecture of an IP over EON.

issue in IP over EON to optimize network performance. The previous related work of VTD has shown notable approaches and interesting conclusions[8,9] in WDM networks, with the objectives of minimizing the cost of transmission and switching equipment. For EON, Zhang *et al.*[10] proposed a novel optical grooming approach to aggregate and distribute traffic directly at the optical layer, while Cai *et al.*[11] investigated the benefit of electronic traffic grooming in IP over EON. The survivable traffic grooming problem for EON was provided in Ref. [12], and Zhang *et al.*[13] proposed a multi-layer auxiliary graph to jointly solve the electrical-layer and optical-layer routing. There are other optimization strategies for multi-layer networks[14], and the network cost is also the only consideration in most of them.

However, the overwhelming growth of Internet traffic also results in the increase in the energy consumption of the network equipment. Energy consumption rather than cost of the network equipment may eventually become a barrier of Internet expansion[15]. Increased energy consumption of the Internet will strengthen the greenhouse effect around the world, and will exacerbate the thermal issue of core network nodes. During the VTD phase, not only the cost but also the power consumption should be considered to achieve a balance[16,17].

We propose an energy-efficient VTD (EE-VTD) scheme in EONs, and formulate a mixed integer linear programming (MILP) model to exactly describe the problem and find the optimal solution. MILP can be widely used to optimize performance of network dimensioning by VTD[18]. We assume that core carrier routers are employed in the IP (virtual) layer, and the multiplexing technology used in the optical (physical) layer is flexible WDM utilizing O-OFDM to adjust spectrum width. The model fully considers the SCC and keeps the performance parameters of elastic OC within thresholds. Part of our work has been introduced in Ref. [19]. A corresponding heuristic algorithm is also proposed for fast computing. The optimization results are presented with perspective analysis. Our main objective is to estimate the potential of IP over EON to preserve energy, and the scalable heuristic algorithm is out of the scope. It shows that the proposed energy efficient IP over EON scheme with VTD can significantly reduce energy consumption over non-VTD scheme, ranging from 11.4% to 27.7%. It is also found that core carrier routers are the major energy consumers which use more than 70% energy.

In order to depict the proposed MILP model and heuristic algorithm explicitly, the cross-layer network statement and assumptions are first introduced and listed below:

1. We consider an IP over EON with an arbitrary topology $G(N, L)$, $N = \{n\}$, $L = \{(i, j)\}$, with $|N|$ nodes and $|L|$ p-links. Each p-link has $|W = [1, nW]|$ spectrum slot, and each slot has the capacity of C (in GHz). $D_{i,j}$ refers to the link length.
2. An OC, standing for a lightpath from an add port to a drop port, can take one or more contiguous slots on one or more p-links with the consistency constraint. Virtual links (v-links), denoted as $V = \{(p, q)|\ p, q \in N, p \neq q\}$, can be set between any two nodes and seen as a hop in virtual layer. It should be noted that with split-spectrum approach proposed in Ref. [5], each v-link can be laid on one or more independent OCs with sufficient bandwidth in total. In our approach, each v-link can be split into at most nK independent branches, with $K = [1, nK]$ predetermined.
3. Each v-link is composed of one or more IP connections, and the speed of each IP port is predefined as U (in Gbps). The set of node pairs is denoted as $R = \{(s, d)\ |s, d \in N, s \neq d\}$, and IP traffic can be laid between any node pairs. The traffic demand matrix is denoted as $T = \{t_{s,d}\}$.
4. The set of supported modulation format F is predefined, and for each $f \in F$, there is a fixed ratio $r_f \in R$ between bit rate (in Gbps) and spectrum width (in GHz). We choose the maximum transmission distance $dm_f \in Dm$ of an OC, which is determined by the modulation format, to represent the transmission performance constraint due to the physical nature of optical signal. It should be noted that other quality of transmission (QoT) constraints could also be accepted by our model, if they can be represented as linear constraint functions.
5. EDFAs are deployed on p-links to regenerate the optical signal. The maximum span distance that optical signal could transmit without regeneration is predefined as De. For each degree of an optical node, a pre-amplifier and a post-amplifier are also equipped.
6. Energy is primarily consumed by three types of components: IP ports, transponders, and EDFAs. The average power consumption of one of these components is predefined as E_{IP}, E_{TR}, and E_{ED}, respectively.
7. The guard bands between contiguous OCs are ignored, for the reason that there can be seen as a part of bandwidth demands to simplify the model.

Then we present the MILP model with a set of decision variables and constraints for the optimal EE-VTD solution following as

$y_{p,q}^{s,d}$ non-negative integer: $y_{p,q}^{s,d}$ denotes the bandwidth demand of the traffic $t(s, d)$ laid on v-link (p, q).

$x_{i,j,w,f}^{p,q,k}$ binary variable: $x_{i,j,w,f}^{p,q,k}$ equals 1 only if the kth OC of v-link (p, q) occupies slots w on link (i, j), and adopts modulation format f. Otherwise it equals 0.

$yn_{p,q}$ non-negative integer: $yn_{p,q}$ denotes the number of IP ports needed to transmit IP traffic between nodes p and q via v-link (p, q).

$xn^{p,q,k}$ binary variable: $xn^{p,q,k}$ equals 1 only if the kth OC of v-link (p, q) carries traffics, otherwise it equals 0.

$en_{i,j}$ non-negative integer: $en_{i,j}$ denotes the number of EDFAs deployed for p-link (i, j).

Minimizing the total power consumption implies minimizing the power consumption from IP ports, transponders, and EDFAs. These three parts are evaluated by

$$2E_{\mathrm{IP}}\sum_{(p,q)\in V} yn_{p,q} + 2E_{\mathrm{TR}}\sum_{(p,q)\in V, K\in K} xn^{p,q,k} + 2E_{\mathrm{ED}}\sum_{(i,j)\in L} en_{i,j}\,. \quad (1)$$

where the multiplier “2” counts a pair of each component.

The virtual layer can be viewed as a general packet switched networks, in which the flows arriving at a node should equal the flows leaving the node. This constraint is called flow conservation and is shown as

$$\sum_{(o,p)\in V} y^{s,d}_{o,p} = \sum_{(p,q)\in V} y^{s,d}_{p,q}, \forall (s,d)\in R, p,\in N\setminus\{s,d\}. \quad (2)$$

The traffic demands between node pair (s and d) must be added at node s and dropped at node d, and can be split as K sub-flows, which is specified as

$$\sum_{(s,q)\in V} y^{s,d}_{s,q} = t_{s,d}, \sum_{(q,s)\in V} y^{s,d}_{q,s} = 0, \forall (s,d)\in R, \quad (3)$$

$$\sum_{(p,d)\in V} y^{s,d}_{p,d} = t_{s,d}, \sum_{(d,p)\in V} y^{s,d}_{d,p} = 0, \forall (s,d)\in R. \quad (4)$$

The physical layer consists of an EON with physical constraints whose demand comes from the virtual layer. Modulation formats and EDFAs are also considered in the physical layer.

The spectrum consistency constraint[20] implies that an OC should be laid over the same range of spectrum along the links allocated to it. It is the same as the flow-conservation constraint applied to each frequency units, as

$$\sum_{k\in K,(p,j)\in L w\in W, f\in F} r_f C x^{p,q,k}_{p,j,w,f} \ge \sum_{(s,d)\in R} y^{s,d}_{p,q},$$
$$\sum_{k\in K,(j,p)\in L w\in W, f\in F} x^{p,q,k}_{j,p,w,f} = 0, \forall (p,q)\in V, \quad (5)$$

$$\sum_{k\in K,(i,q)\in L w\in W, f\in F} r_f C x^{p,q,k}_{i,q,w,f} \ge \sum_{(s,d)\in R} y^{s,d}_{p,q},$$
$$\sum_{k\in K,(q,i)\in L w\in W, f\in F} x^{p,q,k}_{q,i,w,f} = 0, \forall (p,q)\in V, \quad (6)$$

$$\sum_{(i,j)\in L} x^{p,q,k}_{i,j,w,f} = \sum_{(j,o)\in L} x^{p,q,k}_{j,o,w,f}, \forall (p,q)\in V, k\in K,$$
$$j\in N\setminus\{p,q\}, w\in W, f\in F. \quad (7)$$

To express if–then relationship under MILP, a large number B is introduced which is larger than all the possible values of the other side of the equation. Then the spectrum contiguity constraint can be expressed as: for each traffic demand on each link, the spectrum is scanned from lower frequency units to higher frequency units one by one. If the former one is occupied but the latter one is empty, all the subsequent frequency units cannot be occupied by this traffic demand, and is shown as

The capacity constraint guarantees that one spectrum slot serves at most one OC, shown as

$$\sum_{(p,q)\in V k\in K, f\in F} (x^{p,q,k}_{i,j,w,f} + x^{p,q,k}_{j,i,w,f}) \le 1, \forall (i,j)\in L, w\in W. \quad (9)$$

These two terms indicate bidirectional connections.

The split-spectrum scheme implies that each branch of a v-link is modeled as a unicast OC with the unique modulation format as

$$B*(1-x^{p,q,k}_{i,j,w,f}) \ge \sum_{\substack{(i,j_2)\in L: j_2\ne j\\ w_2\in W, f_2\in F}} x^{p,q,k}_{i,j_2,w_2,f_2} + \sum_{\substack{w_2\in W\\ f_2\in F: f_2\ne f}} x^{p,q,k}_{i,j,w_2,f_2} \forall (p,q)\in V,$$
$$k\in K, (i,j)\in L, w\in W, f\in F. \quad (10)$$

Thus we can control the physical characteristics of each OC.

Here we assume that optical signals can only be transmitted within a limited range dm_f under a determinate modulation format. This constraint is shown as

$$\sum_{(i,j)\in L} D_{i,j} x^{p,q,k}_{i,j,w.f} \le dm_f \forall (p,q)\in V, k\in K, w\in W, f\in F, \quad (11)$$

which be replaced by any other linear constraints on QoT[21].

Due to the fixed line-rate feature of IP ports, there may be a bundle of IP ports deployed in the terminals of a v-link to provide sufficient virtual layer capacity for the traffic demand. Thus, the relationship between the number of IP port pairs ($yn_{p,q}$) and the total offered demand on v-link (p, q) is shown as

$$Ryn_{p,q} \ge \sum_{(s,d)\in R} y^{s,d}_{p,q}, \forall (p,q)\in V. \quad (12)$$

$xn^{p,q,k}$ represents the state of the kth branch of v-link (p and q) that if the bandwidth demand laid on (p, q, and k) is non-zero, $xn^{p,q,k}$ equals 1, otherwise $xn^{p,q,k}$ equals 0. If there is no traffic laid on (p, q, and k), the relationship is constrained by the object equation:

$$B*xn^{p,q,k} \ge \sum_{\substack{(i,j)\in L\\ w\in W, f\in F}} x^{p,q,k}_{i,j,w,f}, \forall (p,q)\in V, k\in K. \quad (13)$$

Given the maximum span distance De between two neighboring EDFAs, the relationship between p-link length and the number of EDFA pairs deployed at this p-link can be represented as

$$De.en_{i,j} \ge (D_{i,j} + 2De).xn^{p,q,k}, \forall (p,q)\in V, k\in K. \quad (14)$$

Note that the additional two EDFA pairs count a pre-amplifier and a post-amplifier at the two ends of a p-link.

Due to the computing intensity, the proposed MILP model is merely suitable for small network topologies. In order to efficiently design virtual topologies (VGs) on large optical substrates, we also proposed a heuristic algorithm for EE-VTD (Algorithm 1). The heuristic separates the construction of VG from the resource allocation to reduce the complexity while keeping the efficiency.

$$B*(1-x^{p,q,k}_{i,j,w,f} + x^{p,q,k}_{i,j,w+1,f}) \ge \sum_{w_2\in w+2..nw} x^{p,q,k}_{i,j,w_2,f}, \forall (p,q)\in V, (i,j)\in L, w\in 1..nW-2, f\in F. \quad (8)$$

Algorithm 1: Energy efficient heuristic VTD algorithm

1. Sort the traffic demands from the highest to the lowest, and store them in TQ
2. Create an empty VG
3. For t in TQ do
4. Try to route t over VG
5. If SUCCESS do
6. Allocate resource in VG for t
7. Else // FAILURE
8. Establish a new v-link to directly connect the two ends of t to carry it
9. End if
10. End for
11. Route all the v-links in VG over the PG
12. Compute the total power consumption

In order to evaluate the energy efficiency of the proposed VTD scheme, we studied the following five schemes. The first one is the non-VTD scheme, which makes the VG the same as the physical topology (PG). The second and third are the proposed EE-VTD schemes with $K = 1$ and $K = 2$, respectively. The fourth and fifth are the full-VTD schemes with which traffic demands are laid directly on OCs, also with $K = 1$ and $K = 2$, respectively. Schemes 1, 4, and 5 are set for contrast.

We studied these schemes under the test network topologies as shown in Fig. 2, which are denoted as the 6-node 9-link (N6L9) topology and the NSFNet topology. For NSFNet, we merely give the result of heuristic algorithm due to the computing intensity of the MILP model. Link lengths are marked on the topologies. For each node pair, there is 100% opportunity to carry traffic in the N6L9 network and 50% in NSFNet. The traffic demand is randomly generated. The average demand $\overline{t}$ is picked up successively from the set {20, 40, 60, 80, 100, 120} (Gbps), and is set the same for each node pair in a test. The demand between each node pair is then randomly generated under a uniform distribution within the range $[\overline{t} - 20, \overline{t} + 20]$ (Gbps).

Other parameters are listed in Table 1. We implement our MILP model utilizing the Optimization Programming Language and run the program in IBM ILOG CPLEX Optimization Studio 12.2[22] on an IBM X3650 server. The heuristic algorithm is designed using C++ running in Visual Studio 2013. Note that the power consumption of each IP port is based on the data sheet of Cisco ASR 9001 router (425 W/4 ports)[23]. Due to the immaturity of bandwidth-variable transponders and EDFAs, the power consumption of these components is simulated by typical conventional devices[24].

Figure 3 shows the total power consumption of the N6L9 network under different VTD schemes using both MILP and heuristic methods. It is shown that compared with non-VTD scheme, both EE-VTD and full-VTD can significantly reduce the power consumption. Besides, though the difference between EE-VTD and full-VTD is trivial, the proposed EE-VTD performs better than full-VTD, due to its flexibility in deciding the way to carry traffic (either by OC or by IP hops). By applying the EE-VTD scheme, we can save power consumption from 11.4% to 27.7%, while the average traffic demand grows from 20 to 120 Gbps. It is also found that the total power consumption grows approximately linearly with the increase in average demand, which implies the linear scaling feature of network power consumption.

In Figs. 4 and 5, the power consumption of different components is contrasted. The results of N6L9 are obtained by MILP, whereas the results of NSFNet are by heuristic. It shows that IP layer consumes

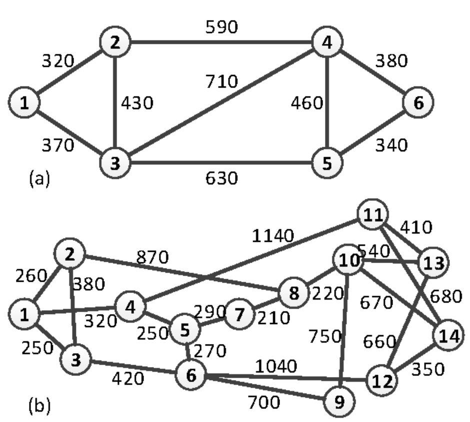

Fig. 2. (a) N6L9 topology. (b) NSFNet topology.

Table 1. MILP Parameters

nW	16
C (GHz)	12.5
F	PDM-BPSK, PDM-QPSK, and PDM-8QAM
R (bps/Hz)	2, 3, 4
dm (km)	1500, 1000, 500
De (km)	80
U (Gbps)	10
E_{IP} (W)	106
E_{TR} (W)	73
E_{ED} (W)	14

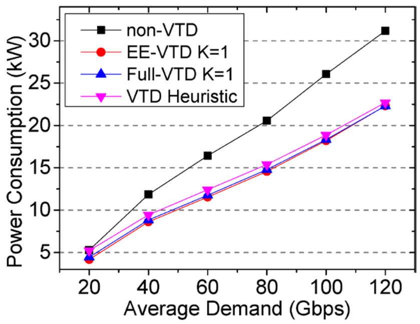

Fig. 3. MILP optimization solutions for non-VTD, EE-VTD, full-VTD, and heuristic.

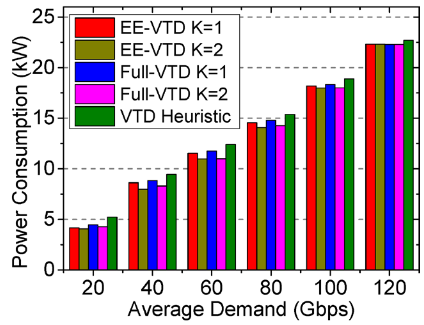

Fig. 6. Comparison between different maximum v-link branch numbers (K).

the highest percentage (72%–91% on N6L9 and 69%–92% on NSFNet) of the total power which is in the great majority. We can infer that the EON is an energy-efficient network compared with IP.

Figure 6 shows the relationship between the maximum branch number of each v-link and the total power consumption on the N6L9 topology. The results show that the split-spectrum approach almost has no effect on energy conservation, for the reason that it requires more network component to achieve the split-spectrum capability.

Power consumption will become a serious issue in future Internet which relies on IP over EON architecture. It is important to analyze and find out the features of network power consumption and to explore energy-efficient networking models for IP over EON.

In conclusion, we develop MILP models and a heuristic algorithm for this issue, and several interesting features are highlighted. The proposed model can significantly reduce power consumption from 11.4% to 27.7%.

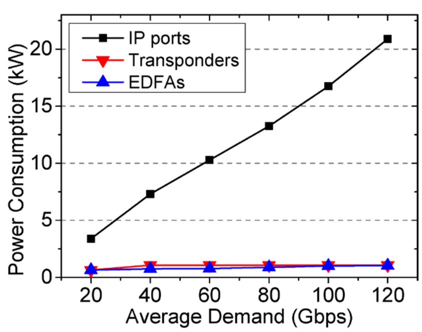

Fig. 4. Power consumption of different types of components on the N6L9 topology using the MILP model.

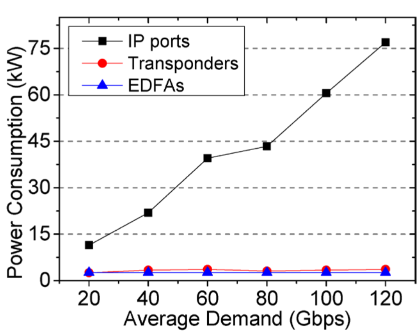

Fig. 5. Power consumption of different types of components on the NSFNet topology using the heuristic algorithm.

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