Energy optimization in IP-over-WDM networks

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ABSTRACT

The energy crisis and environmental protection are gaining increasing concern in recent years. ICT (Information and Communication Technology) has a significant impact on the total electricity consumption all over the world. Telecom networks, being an important part of ICT, consume significant energy since more network equipment is deployed annually. Specifically, in IP-over-WDM networks, energy is consumed by network elements at both IP and WDM layers. Routers in the IP layer are the largest energy consumer in this architecture, and current network infrastructures have no energy-saving scheme, so a large amount of energy is wasted when traffic load is low. In this paper, we propose a novel approach to save energy in IP-over-WDM networks by shutting down idle line cards and chassis of routers based on time-of-the-day network traffic variation. A method based on Mixed Integer Linear Programming (MILP) is proposed to ensure that the energy cost incurred by the IP routers and optical cross-connects is minimized by our approach. We also propose some possible approaches to minimize potential traffic disruption when the network elements are shut down.

1. Introduction

Energy efficiency has been gaining increasing interest in our society in recent years. In particular, energy consumption of ICT (Information and Communication Technology) is increasing fast, since more equipment for networking and communication is being deployed annually. From the data of 2009, ICT consumes about 8% of the total electricity all over the world [1]. Although this percentage is not high, the energy consumption of ICT is still considerable because the total amount of electricity usage in the world is enormous. Telecom networks, which represent a significant part of the ICT, are penetrating further into our daily lives. The traffic volume of broadband telecom networks is increasing rapidly and so is its energy consumption. Considering both the growing energy price (expected with the decline of availability of cheap fossil fuels) and the increasing concern on the greenhouse effect, the energy consumption of ICT is already raising questions. It is imperative to develop energy-efficient telecom solutions. We need to design new networking paradigms so that telecom networks will maintain the same level of functionality while consuming less energy in future.

IP-over-WDM is a promising network architecture for next-generation telecom networks. In an IP-over-WDM network, energy is consumed in both electronics (e.g., IP) and optics (e.g., WDM). IP routers, switches, network gateways, etc. consume most of the energy in electronics (which is loosely referred to as the IP layer here), while optical cross-connects (OXC)\textregistered, EDF\textregistered, and transmitters are the main energy consumers in optics (which is loosely referred to as the physical layer). According to recent research of energy efficiency, electronic devices in the IP layer, especially routers, consume much more energy than optical devices in the physical layer [2]. Therefore, saving
energy at the IP layer should be very beneficial to this two-layer network infrastructure.

Traffic load in an IP-over-WDM network is always varying as a consequence of users’ behavior over various times of the day. However, in current telecom networks, energy consumption of network equipment is not considered as a critical issue so that majority of the IP routers of the network are kept powered-on day and night without concerning their levels of utilization. In this case, a large amount of energy is wasted when the traffic load is low. To improve this situation, in this paper, we propose a novel scheme to reduce the energy consumption of IP-over-WDM networks, especially in the IP layer, according to the traffic variation during the time of the day. When the traffic load is low (at night or in early morning), line cards and chassis of IP routers can be of very low utilization or idle. In this case, we shut the idle line cards and chassis down and reroute the affected traffic, thereby saving the energy consumed by them. If all the line cards of a chassis are shut down in our scheme, we also shut down this chassis to save the energy consumed by this idle chassis. On the contrary, if traffic load increases and additional line cards and chassis are needed, we turn them on. When this equipment is being shut down or turned on, traffic interruption may occur since re-routings are needed. In this case, our approach is also focusing on minimizing the amount of reconfiguration of network elements and reroutings, so that potential traffic interruptions can be minimized.

This paper is organized as follows: Section 2 introduces related work published in recent years; Section 3 formally states the problem; Section 4 proposes a method based on Mixed Integer Linear Programming (MILP) to minimize the network-wide energy cost and potential traffic disruptions; Section 5 provides numerical results; and Section 6 concludes the paper.

2. Related work

Recently, more and more literature has been published on energy efficiency in telecom networks. In general, the related works can be divided into three categories: energy-efficient network design, green traffic grooming, and selectively turning down network elements.

On “energy-efficient network design”, the authors in [3] propose an approach of network design and planning which minimizes energy consumption of IP-over-WDM networks by studying energy usage of components in both IP and physical layers and using total energy consumption as the objective of network design.

On “green traffic grooming”, in [4], total energy consumption of an optical WDM network is modeled in terms of the energy consumed by individual lightpaths. An ILP (Integer Linear Program) formulation of the energy-aware grooming problem is defined. In [5], the authors propose both an MILP and a heuristic approach to solve the routing and wavelength assignment and decrease the number of lightpath interfaces in order to minimize the energy consumption of the network. In [6], the authors consider the energy consumed by each network operation needed while grooming traffic in optical backbone networks. Energy consumption of every operation in traffic grooming is investigated, and an auxiliary-graph based model is proposed to identify the energy consumed by the operations. Results show that energy-aware traffic grooming saves a significant amount of energy compared to the traditional traffic grooming scheme. In [7], the authors focus on the energy-aware dynamic traffic grooming problem in optical networks, with the methodology of auxiliary graph.

As for “selectively turning down network elements”, the authors in [8] propose a scheme to reduce energy consumption by switching off idle physical nodes and links in a hierarchical network topology according to the traffic variation during time of the day. But shutting down physical nodes or links may lead to much longer routes for some traffic demands, so the performance of the whole network may be affected. The authors in [9] also propose an approach to selectively switching off optical links. Furthermore, in [10], a scheme is proposed to shut down idle line cards (and corresponding optical circuit, or lightpath, associated with the line cards) when the traffic load is low. Note that shutting down lightpaths may lead to undesirable traffic disruptions but this problem is not addressed. As a further difference with respect to [10], in our approach, when traffic load is low, we shut down not only idle line cards, but also the chassis of IP routers. This will lead to: changes only in the virtual-network connectivity, without affecting the underlying physical topology. Also, we minimize the amount of network reconfigurations, such as reconfiguration of connectivity of line cards and lightpaths, to minimize the potential traffic disruption when the line cards and chassis of IP routers are being shut down. In addition, we also consider minimizing the energy consumption from OXCs in the network.

Today, telecom networks are going through technological changes to support enormous data traffic while controlling their energy consumption. Our research is a timely one which can enable carriers to design energy-efficient networks (and their energy-efficient upgrade) by dynamically reconfiguring network devices, i.e., shutting down idle network elements to save energy, ensuring a minimal impact on the living traffic served by the network.

3. Problem statement

3.1. Motivation of time-aware energy optimization

Traffic load in telecom networks is determined by the behavior of users who are using the network. In general, most enterprise and residential network users access the Internet in the daytime or evening, respectively, which induces high bandwidth utilization of the network concentrated in some specific times of the day. On the contrary, during early morning or after midnight, the traffic demand by users reduces significantly to a much lower level.

Some institutions have done some investigations on user behaviors of the telecom networks. As an example, Fig. 1 shows the real-time traffic load variation of Internet in Netherlands during time of the day. It is measured by service provider AMS-IX in Amsterdam [11]. From 6:00 to 16:00, the traffic load increases continuously. It is because
most activities of enterprise users happen during this time. Then, from 16:00 to 20:00, the traffic load increases a little faster because residential users begin to access the Internet while some of the enterprise users are still connecting to the network. Then, from 20:00 to 6:00, the traffic load decreases rapidly, because the users from both enterprise and residential area are going to sleep. The ratio of maximum load and minimum load is about 4:1, which is very large.

In traditional telecom networks with no energy-saving mode, network capacity is dimensioned to support peak-hour traffic and IP routers and switches are always powered-on day and night, ready for routing/switching traffic, even though some line cards and chassis may be idle for a considerable time. According to the traffic profile shown in Fig. 1, if there is an approach which is able to shut down idle network elements during off-peak hours, ideally 75% of energy can be saved when the traffic load decreases to its minimal value around 6:00.

3.2. Different schemes of lightpath bypass and their energy consumption

An IP-over-WDM network has a two-layer network infrastructure, which is shown in Figs. 2a–2c. Routers at the IP layer can be interconnected by virtual connections, while OXCs at the physical layer connect to each other by fibers and compose the physical topology. Each router at the IP layer is connected to a corresponding OXC at the physical layer.

When we consider traffic grooming and routing, there are three different methods of establishing lightpaths, i.e., without lightpath bypass (for short, non-bypass), direct lightpath bypass (for short, direct bypass) and multi-hop lightpath bypass (for short, multi-hop bypass) [3]. Fig. 2a shows a connection between node a and node d using the non-bypass scheme. In this scheme, routers and OXCs at intermediate node b and node c are not allowed to be bypassed. In other words, three lightpaths (A–B, B–C, and C–D) have to be established in the physical topology and three virtual connections (a–b, b–c, c–d) have to be established in the IP layer. In this case, besides node a and node d, line cards and chassis of the routers at node b and node c have to be used to transfer and process traffic, which consumes energy.

Fig. 2b shows a connection between node a and node d using the direct bypass scheme. In this scheme, routers and OXCs at intermediate node b and node c are able to be bypassed. In other words, only one lightpath (A–D) is needed to be established in the physical topology and only one virtual connection (a–d) is needed to be established in the IP layer. In this case, line cards and chassis of the router at node b and node c are not used to transfer and process traffic. We can shut them down to save energy. However, if there is another traffic demand from node a to node b, a new lightpath from node A to node B has to be established. Therefore, additional overhead of energy consumption may occur [6], while in non-bypass scheme, the traffic demand from node a to node b can be groomed to the existing light path from node A to node B.

Considering the advantages and disadvantages of non-bypass and direct bypass, the third scheme — multi-hop bypass is more flexible. Fig. 2c shows a connection between node a and node d using the multi-hop bypass scheme. It is a combination of the previous two schemes. The router at node b is used for transferring and processing traffic, and the router at node c is bypassed. In other words, two lightpaths (A–B, B–D) are established in the
physical topology, and two virtual connections \((a-b, b-d)\) are established in the IP layer. In this case, the lightpath between node \(A\) and node \(B\) can be used for grooming new traffic, while line cards and chassis of the router at node \(C\) can be shut down for energy saving.

4. Proposed optimization method

4.1. Energy-optimization scheme

Considering the characteristics of the three different schemes for traffic grooming described in Section 3, we apply the multi-hop bypass approach, the most flexible one, for our routing and wavelength assignment.

Besides, in order to simulate the traffic-load variation during the day, we simplify the real traffic profile in Fig. 1 with the step function shown in Fig. 3. The function in Fig. 3 expresses the trend of traffic variation during the day and maintains the ratio between the maximum and minimum traffic. We assume that, in our simplified scenario, the traffic demand is static in each time period, i.e., 2 h durations.

Then, during each time period, we use a Mixed Integer Linear Programming (MILP) approach to minimize the total energy consumption of line cards and chassis of IP routers and also OXC in the network, and shut down the idle line cards and chassis of IP routers so that maximal amount of energy is able to be saved. (OXC do not need to be shut down because the next-generation all-optical OXC consume much less energy than the routers, though we also try to minimize the energy consumption of OXC).

This paper deals with a static network planning problem. It is intended to be run off-line based on predicted traffic variation during the time of the day. So every single value in our traffic matrices (e.g., Table 1) is a predicted average value of traffic demand (in the unit of Gbps) from one source node to one destination node and, we do not focus on how many traffic demands of lower granularity compose this average traffic demand in the traffic matrix or what the duration of each traffic demand is. In this context, when the traffic load changes from one level to another, some traffic demands (e.g., those lasting for the entire day) may have to “suffer from” traffic disruption caused by re-routings applied to minimize energy. However, we are not addressing here the minimization of the exact amount of traffic-flow disruptions since we do not specify the duration of each smaller-granularity traffic demand. Therefore, potential traffic disruptions may happen at the moment that we are shutting down or turning on working line cards and chassis when traffic load changes in this context.

However, we are able to measure the amount of reroutings of traffic and reconfigurations of lightpaths, line cards and chassis when traffic load changes from one to another. We assume that less reconfiguration and less reroutings lead to less traffic disruption in the realistic networks.

We propose three different schemes to demonstrate different performance of minimizing energy consumption and traffic disruption.

(a) Unconstrained Reconfiguration

In this scheme, we run MILP to obtain the minimal energy consumption of the network in each 2 h time period and reconfigure the lightpath, line cards, chassis, etc., without any constraint which jointly considers the neighboring time periods. In other words, the configurations of lightpath, line cards, chassis, etc. of the network are independent in each 2 h time period.

(b) Virtual-Topology-Constrained Reconfiguration

We modify the MILP in scheme (a) by adding some constraints considering the relationship between two neighboring time periods. In order to reduce the reconfiguration of the network and rerouting of the traffic, we use a top–down scheme to establish and remove the lightpaths, minimizing the reconfiguration of lightpaths, line cards and chassis. In this scheme, we first run MILP to calculate the minimal number of line cards and chassis which are needed to support the traffic demand during traffic peak time. Based on the results of traffic peak time, we calculate the number of line cards and chassis for traffic off-peak time. Using a sequential top–down scheme (also shown in Fig. 3), we reconfigure the set of lightpaths, line cards and chassis under lower traffic load so that they are sub-sets of the ones under higher traffic load.

This operation requires additional constraints in energy optimization, but allows us to reduce the number of reconfiguration operations, and, in return, to reduce the potential traffic interruption while the traffic is being rerouted while moving from one load level to another. In this context, when the traffic load decreases, we shut down line cards and chassis of IP routers which are no longer used, and no additional line cards or chassis need to be turned on. On the other hand, when the traffic load increases, we turn on additional line cards and chassis which are needed to be used while no line cards or chassis need to be shut down.

(c) Full-Constrained Reconfiguration

Full-Constrained Reconfiguration also use the top–down scheme mentioned in Virtual-Topology-Constrained Reconfiguration. However, this kind of reconfiguration not only applies the constraints of the subset to lightpaths, line cards and chassis in lower traffic load, but also applies the constraints of the subset to traffic flows in the virtual topology and physical routings in the physical topology. This scheme, to the full extent, minimizes the reconfiguration of network and rerouting of traffic. This scheme imposes even more additional constraints in energy optimization than Virtual-Topology-Constrained Reconfiguration and, as a consequence, the total energy consumption of the network may be larger.

4.2. Mathematical formulation

Based on the simplified traffic profile in Fig. 3 and the energy-optimization schemes provided by Section 4.1, we use Mixed Integer Linear Programming (MILP) to formulate and solve this problem. By line cards we mean line cards in routers only. The notations are shown as follows:

**Given.**

\[ G(N, E) \quad \text{Network topology.} \]

\[ N \quad \text{Set of nodes in the network.} \]

\[ E \quad \text{Set of edges in the network.} \]

\[ W \quad \text{Set of wavelengths in a fiber.} \]
Fig. 3. Simplified graph of traffic load and the top–down scheme.

\[ P_{mn} \] Number of fibers from node \( m \) to node \( n \).

\[ \Lambda_{sd} \] Traffic demand from node \( s \) to node \( d \).

\( C \) Capacity of each wavelength channel.

\( V_{ij} \) Number of lightpaths from node \( i \) to node \( j \) in the virtual topology under higher traffic load.

\( q'_{ij} \) Number of transmitting line cards at node \( i \) corresponding to \( V'_{ij} \) (under higher traffic load). It is also equal to the number of receiving line cards at node \( j \) corresponding to \( V'_{ij} \). (There is only one interface per line card, either for transmitting or for receiving, so there are line cards from both sides corresponding to \( V'_{ij} \)).

\( B \) Bandwidth of a line card.

\( L \) Number of slots in the chassis of router.

\( E_{el} \) Energy consumption of a line card in an IP router.

\( E_{ec} \) Energy consumption of a chassis in an IP router.

\( E_{o} \) Energy consumption of a connection in an Optical Cross-connect.

\( V_{ij,w} \) Number of lightpaths established from node \( i \) to node \( j \), which use wavelength channel \( w \) (under higher traffic load).

\( \lambda'_{ij} \) Traffic flowing from node \( s \) to node \( d \), employing \( V_{ij} \) as an intermediate lightpath (under higher traffic load).

\( p'_{ij,w} \) Number of lightpaths between nodes \( i \) and \( j \), being routed through fiber link \( mn \), and using wavelength channel \( w \) (under higher traffic load).

\( n_{w}(i) \) Number of working chassis in node \( i \).

\( n_{c}(i) \) Number of working line cards in node \( i \).

\( q_{ij} \) Number of transmitting line cards at node \( i \) corresponding to \( V_{ij} \). It is also equal to the number of receiving line cards at node \( j \) corresponding to \( V_{ij} \). (There is only one interface per line card, either for transmitting or for receiving, so there are line cards from both sides corresponding to \( V_{ij} \)).

\( \lambda_{ij} \) Number of lightpaths between nodes \( i \) and \( j \), being routed through fiber link \( mn \), and using wavelength channel \( w \).

\( q_{ij} \) Number of lightpaths established from node \( i \) to node \( j \), which use wavelength channel \( w \) (under higher traffic load).

\( \lambda_{ij} \) Traffic flowing from node \( s \) to node \( d \), employing \( V_{ij} \) as an intermediate lightpath (under higher traffic load).

\( p_{ij,w} \) Number of lightpaths between nodes \( i \) and \( j \), being routed through fiber link \( mn \), and using wavelength channel \( w \).

\( \Lambda_{sd} \) Traffic demand from node \( s \) to node \( d \).

\( C \) Capacity of each wavelength channel.

\( V_{ij} \) Number of lightpaths established from node \( i \) to node \( j \).

\( q'_{ij} \) Number of transmitting line cards at node \( i \) corresponding to \( V'_{ij} \). It is also equal to the number of receiving line cards at node \( j \) corresponding to \( V'_{ij} \). (There is only one interface per line card, either for transmitting or for receiving, so there are line cards from both sides corresponding to \( V'_{ij} \)).

\( w \) Wavelength ID in a fiber.

\[ \text{Minimize.} \]

\[ \sum_{i} \left[ E_{el} \times n_{w}(i) + E_{ec} \times n_{c}(i) \right] + E_{o} \times \sum_{w} \sum_{i,j} \left( \sum_{m,n} p_{ij,w}^{mn} + V_{ij,w} \right). \] (1)

\[ \text{Constraints.} \]

\[ \sum_{j} \lambda_{ij} - \sum_{j} \lambda'_{ij} = \begin{cases} \Lambda_{sd} & i = s \\ - \Lambda_{sd} & i = d \\ 0 & i \neq s, d \end{cases} \forall i, s, d \in N \] (2)

\[ \sum_{sd} \lambda_{ij} \leq C \times V_{ij} \forall i, j \in N \] (3)

\[ \sum_{n} p_{ij,w}^{mn} - \sum_{n} p_{ij,w}^{mn} = \begin{cases} V_{ij,w} & m = i \\ -V_{ij,w} & m = j \forall i, j, m \in N, \forall w \in W \\ 0 & m \neq i, j \end{cases} \] (4)

\[ \sum_{w} V_{ij,w} = V_{ij} \forall i, j \in N \] (5)

\[ \sum_{w} p_{ij,w}^{mn} \leq p_{mn} \forall (m, n) \in E, \forall w \in W \] (6)

\[ V_{ij} \leq V_{ij}' \forall i, j \in N \] (Applied for Virtual-Topology-Constrained Reconfiguration) (7)

\[ q_{ij} \leq q'_{ij} \forall i, j \in N \] (Applied for Virtual-Topology-Constrained Reconfiguration) (8)

\[ q_{ij} \geq \left( \sum_{sd} \lambda_{ij} \right) / B \forall i, j \in N \] (9)

\[ n_{w}(i) = \sum_{j} (q_{ij} + q_{ji}) \forall i \in N \] (10)

\[ n_{c}(i) \geq \frac{1}{E_{o}} \sum_{j} (q_{ij} + q_{ji}) \forall i \in N \] (11)

\[ V_{ij,w} \leq V_{ij,w} \forall i, j \in N, \forall w \in W \] (Applied for Full-Constrained Reconfiguration) (12)

\[ \lambda_{ij} \leq \lambda_{ij}' \forall i, j, s, d \in N \] (Applied for Full-Constrained Reconfiguration) (13)

\[ p_{ij,w}^{mn} \leq p_{ij,w}^{mn} \forall i, j \in N, (m, n) \in E, \forall w \in W \] (Applied for Full-Constrained Reconfiguration) (14)

The formulation is based on the multi-hop lightpath bypass scheme introduced in Section 3.2. Eq. (1) gives the objective function, which minimizes the total energy consumed by line cards and chassis of routers in electrical layer and optical cross-connects in the optical layer of the IP-over-WDM networks. The highlighted part of the equation: “\( E_{o} \times \sum_{w} \sum_{i,j} \left( \sum_{m,n} p_{ij,w}^{mn} + V_{ij,w} \right) \)” denotes the energy consumed by optical cross-connects, which is determined by the total number of physical connections.
Eq. (2) is the multicommodity-flow-based equation governing the flow of traffic in the virtual topology at the IP layer [12]. Eq. (3) specifies the capacity constraint in the virtual-topology links (lightpaths). Eqs. (4) and (5) are the multicommodity-flow-based equations governing the routing of lightpaths over the physical topology from source to destination, while using wavelength channel $w$ [12]. These constraints ensure the wavelength continuity through all-optical OXCs. Eq. (6) ensures that the total number of lightpaths using the physical link $mn$ and wavelength channel $w$ is not greater than the number of fibers, i.e., one wavelength channel can carry only one lightpath.

Eqs. (7) and (8) are applied only by the Virtual-Topology-Constrained Reconfiguration introduced in Section 4.1. They denote that the set of working lightpaths and line cards when traffic load is lower should be the subset of working lightpaths and line cards when traffic load is higher. We use a first-fit method to assign $V_q$ and $q_{ij}$ so that “$V_q$ is a subset of $V_j$” corresponds to “$V_q \leq V_j$”, and “$q_{ij}$ is a subset of $q_{ij}’$” corresponds to “$q_{ij} \leq q_{ij}’$”. Therefore, as shown in Fig. 3, we first calculate the values of $V_q$ and $q_{ij}$ for the traffic demand of peak time, i.e., at 20:00–22:00 in Fig. 1, and then use this value of $V_q$ and $q_{ij}$ as the given parameter $V_q’$ and $q_{ij}’$ for the next or the previous lower traffic, i.e., at 22:00–0:00 or 18:00–20:00. After that, we continue to go “down step” for calculation until the lowest traffic level.

Eq. (9) accounts that $q_{ij}$ is equal to “the total traffic flow on lightpath from node $i$ to $j$” divided by the bandwidth of a line card. Note that this count holds since we assume a first-fit scheme to assign the traffic into the line cards. The operator “$\geq$” equals the ceiling function if we define $q_{ij}$ to be an integer. Eq. (10) denotes that the number of line cards in each node $i$ is equal to the number of line cards used by the flows departing from node $i$ $(q_{ij})$ and arriving at node $i$ $(q_{ji})$, and similarly, Eq. (11) denotes that “the number of chassis used at node $i$” is equal to “the number of line cards used by the flows departing from node $i$ $(q_{ij})$ and arriving at node $i$ $(q_{ji})’” divided by the number of slots in a chassis. Here we also use a first-fit scheme to assign the line cards into the chassis, and use the operator “$\geq$” to denote the ceiling function.

Eqs. (12)–(14) are applied only by the Full-Constrained Reconfiguration scheme. Eq. (12) denotes that the $V_{ij,w}$ (lightpaths established load from node $i$ to node $j$ using wavelength channel $w$) for lower traffic load is the subset of the $V_{ij,w}$ for previous higher traffic load. Similarly, the Eqs. (13) and (14) denotes the $\lambda_{ij}^{sd}$ (traffic flows from node $s$ to node $d$, employing lightpath $V_{ij}$) and $P_{mn}^{ij,w}$ (Number of lightpaths between nodes $i$ and $j$, being routed through fiber link $mn$, and using wavelength channel $w$) for lower traffic load are the subsets of the ones for previous higher traffic load. Note that the Eqs. (7) and (8) are contained logically in Eqs. (12) and (13). Eqs. (12)–(14) are able to ensure the traffic flows, lightpaths, line cards and physical routings for lower traffic load are all the corresponding subsets of the ones for previous higher traffic load so rerouting of traffic is avoided.

Except Eqs. (7), (8), (12)–(14), other equations are applied by all the three schemes, i.e., Unconstrained Reconfiguration, Virtual-Topology-Constrained Reconfiguration and Full-Constrained Reconfiguration.

Based on these formulations, for Unconstrained Reconfiguration, we run the MILP without Eqs. (7), (8), (12)–(14), independently in each time period. For Virtual-Topology-Constrained Reconfiguration, we first run the MILP in peak traffic time without the Eqs. (7), (8), (12)–(14). Then, we use the results of $V_q$ and $q_{ij}$ to be the values of $V_q’$ and $q_{ij}’$ for the lower traffic load and run the MILP again with the Eqs. (7) and (8), in a “top–down” sequence to get the results in off-peak traffic time. Finally, for Full-Constrained Reconfiguration, we first run the MILP in peak traffic time without the Eqs. (7), (8), (12)–(14). Then, we use the results of $V_q’$, $q_{ij}’$, $V_{ij,w}$, $\lambda_{ij}^{sd}$ and $P_{mn}^{ij,w}$ to be the values of the corresponding $V_q$, $q_{ij}$, $V_{ij,w}$, $\lambda_{ij}^{sd}$ and $P_{mn}^{ij,w}$ for the lower traffic load, and run the MILP again with the Eqs. (12)–(14), in a “top–down” sequence to get the results in the off-peak traffic time.

Therefore, the Virtual-Topology-Constrained Reconfiguration constrains the reconfiguration of virtual topology of the network, and ensures that the set of light path, working line cards and chassis at lower traffic load is a subset of the corresponding ones at previous higher traffic load, then the amount of reconfiguration of network elements when traffic load changes is reduced, also leading to a decrease of actual traffic disruptions. However, reroutings may still occur when we reconfigure the lightpaths and line cards in different time period since we do not constrain traffic flows in Virtual-Topology-Constrained Reconfiguration. In this context, the Full-Constrained Reconfiguration eliminates the re-routings of traffic. Besides, since we do not shut down optical links in physical layer, the physical rerouting is not likely to happen when virtual topology is fixed. So the reroutings we are investigated in this paper are the flows rerouted in Virtual Topology.

5. Numerical results

5.1. Energy consumption

To evaluate the performance of our energy optimization scheme, we use a typical enterprise network topology (Fig. 4) for illustration. It has 14 nodes and 21 links, one pair of bidirectional fiber between each neighbor nodes, with 32 wavelengths in each fiber, and capacity of each wavelength channel is 40 Gbps (C). We use a model of a typical enterprise router to capture its energy consumption. The line card of the router has the output bandwidth of 2.5 Gbps (B). We multiplex 16 line
cards of 2.5 Gbps into one 40 Gbps wavelength channel. The energy consumption of the line card is 140 watt ($E_{el}$). The chassis can support at most 16 line cards ($L$) and its energy consumption is 5700 watt ($E_{ec}$, excluding the energy consumption of line cards) [13]. Note that in our case, shutting down line cards and chassis is completely powered off. They will no longer consume energy after being shut down. We also use a model of a typical enterprise OXC (with all-optical switching fabric) to capture its energy consumption. The energy consumption of the OXC is 470 mW per connection ($E_o$) [14].

We use the data of a realistic value of traffic measurement in [15] to generate the traffic matrix (Table 1). We use the realistic traffic matrix in [15] and proportionally scale it to meet the traffic load requirement in Fig. 3. We ensure the total traffic demand of all node pairs in each time period to be equal to the traffic load in Fig. 3. Our problem is a variant of the virtual-topology design problem, which has been shown to be NP-hard [12]. We use a computer with Intel Core2 Quad CPU Q9650 (3.00 GHz) and 4 GB Memory and AMPL/CPLEX to do the computation. It takes about 3 h to obtain each optimization result.

Table 2 shows the results by Virtual-Topology-Constrained Reconfiguration. It demonstrates the amount of energy consumed by line cards, chassis of IP routers, and OXCs when using our scheme to shut down idle line cards and chassis during various time of the day. Note that the trend of the variation of the total energy consumption follows the trend of the traffic variation after our energy-saving scheme. Table 2 also reports the energy saving ratio, which is calculated by comparing the energy consumption by our approach with the energy consumption where line cards and chassis are deployed for peak traffic load (20:00–22:00) and never turned off. The energy savings vary from 0% to 63.5%, with an average value of 31.0%.

The results in Table 2 demonstrate that Virtual-Topology-Constrained Reconfiguration at the IP layer may enable the relevant savings in the energy consumption in IP-over-WDM networks. The results also inform us that the energy consumed by chassis and line cards in IP layer is much more than the energy consumed by OXCs in the optical layer. Hence, shutting down line cards and chassis in IP layer is very efficient to reduce the energy usage in IP-over-WDM networks. Furthermore, the contribution to the energy consumption due to chassis is dominant with respect to line cards, which indicates that an effective energy-saving scheme should also consider shutting down of entire chassis together with line cards. For better visualization, we plot the variation of energy consumption of line cards and chassis of IP routers in Fig. 5. Energy consumption of OXCs is not plotted in the figure (as well as in later illustrations), because it is much smaller than those of the line cards and chassis of IP routers and it is not possible to plot them together clearly. We also plot the variation of energy savings during various times of the day.

More constraints for minimizing the reroutings may lead to worse performance of energy consumption. We compare the energy consumption of Full-Constrained Reconfiguration, Unconstrained Reconfiguration, and Virtual-Topology-Constrained Configuration respectively in Fig. 6. The Full-Constrained Reconfiguration costs 22.36% more energy consumption on average during the time variation of the day. Notably, the Constrained Reconfiguration requires almost the same energy as the Unconstrained Reconfiguration.

5.2. Reconfigurations of lightpaths and line cards

Figs. 7a–7c give a snapshot of the number of established lightpaths, working line cards, and chassis in each node in the scenario by the Virtual-Topology-Constrained Reconfiguration approach. We select three different time periods to demonstrate three different traffic loads, i.e., peak load at 20:00–22:00, minimal load at 6:00–8:00 and intermediate load at 0:00–2:00. The results show that the number of lightpaths, working chassis, and line cards are fewer for every node when the traffic load is lower. These results show that the scheme of subset-constrained introduced in Section 3 does work. Furthermore, the nodes which have higher traffic load, such as, 2, 8, 9, 12, 13, have higher line cards and chassis utilization. (These are also the areas of higher population density in United States.)

Then we compare the reconfigurations of lightpaths and line cards by Full-Constrained Reconfiguration, Virtual-Topology-Constrained Reconfiguration and Unconstrained Reconfiguration. The number of newly established lightpaths, shut-down lightpaths, turned-on line cards, and shut-down line cards by Full-Constrained Reconfiguration, Virtual-Topology-Constrained Reconfiguration and
Table 1
Traffic matrix at peak-load time (20:00–22:00).

<table>
<thead>
<tr>
<th>Node ID</th>
<th>Traffic demands (Gbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>1.811</td>
</tr>
<tr>
<td>4</td>
<td>0.695</td>
</tr>
<tr>
<td>5</td>
<td>12.159</td>
</tr>
<tr>
<td>6</td>
<td>0.182</td>
</tr>
<tr>
<td>8</td>
<td>1.481</td>
</tr>
<tr>
<td>9</td>
<td>1.106</td>
</tr>
<tr>
<td>11</td>
<td>0.185</td>
</tr>
<tr>
<td>14</td>
<td>3.900</td>
</tr>
</tbody>
</table>

Table 2
Energy consumption and energy savings.

<table>
<thead>
<tr>
<th>Time of the day</th>
<th>Energy consumption of Chassis (W)</th>
<th>Energy consumption of Line cards (W)</th>
<th>Energy consumption of Optical Cross-connect (W)</th>
<th>Energy savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6:00–8:00</td>
<td>96,900</td>
<td>26,320</td>
<td>115.15</td>
<td>63.5</td>
</tr>
<tr>
<td>8:00–10:00</td>
<td>108,300</td>
<td>33,880</td>
<td>131.60</td>
<td>57.9</td>
</tr>
<tr>
<td>10:00–12:00</td>
<td>153,900</td>
<td>46,760</td>
<td>156.04</td>
<td>40.6</td>
</tr>
<tr>
<td>12:00–14:00</td>
<td>176,700</td>
<td>58,800</td>
<td>167.79</td>
<td>30.3</td>
</tr>
<tr>
<td>14:00–16:00</td>
<td>182,400</td>
<td>63,280</td>
<td>174.37</td>
<td>27.3</td>
</tr>
<tr>
<td>16:00–18:00</td>
<td>210,900</td>
<td>70,840</td>
<td>183.30</td>
<td>16.6</td>
</tr>
<tr>
<td>18:00–20:00</td>
<td>233,700</td>
<td>78,960</td>
<td>186.59</td>
<td>7.46</td>
</tr>
<tr>
<td>20:00–22:00</td>
<td>250,800</td>
<td>87,080</td>
<td>196.93</td>
<td>0</td>
</tr>
<tr>
<td>22:00–0:00</td>
<td>233,700</td>
<td>78,960</td>
<td>186.59</td>
<td>7.46</td>
</tr>
<tr>
<td>0:00–2:00</td>
<td>193,800</td>
<td>67,200</td>
<td>178.13</td>
<td>22.7</td>
</tr>
<tr>
<td>2:00–4:00</td>
<td>153,900</td>
<td>46,760</td>
<td>156.04</td>
<td>40.6</td>
</tr>
<tr>
<td>4:00–6:00</td>
<td>108,300</td>
<td>33,880</td>
<td>131.60</td>
<td>57.9</td>
</tr>
</tbody>
</table>

Fig. 7a. A snapshot of the established lightpaths at each node by Virtual-Topology-Constrained Reconfiguration.

Unconstrained Reconfiguration, are shown as Figs. 8a, 8b, 9a and 9b, respectively. As these figures show, the Full-Constrained Reconfiguration approach invokes the smallest amount of reconfigurations when traffic load changes, while the Unconstrained Reconfiguration approach invokes the largest one. Virtual-Topology-Constrained Reconfiguration stands in the middle. For example, Fig. 8a shows the number of newly established lightpaths during various time of the day. When traffic load decreases (e.g. from 22:00 to 6:00), no new lightpaths need to be established by the Virtual-Topology-Constrained Reconfiguration approach, while the Unconstrained Reconfig-
Fig. 7c. A snapshot of the number of working chassis at each node by Virtual-Topology-Constrained Reconfiguration.

Fig. 8a. Number of newly established lightpaths.

Fig. 8b. Number of newly shut-down lightpaths.

Fig. 9a. Number of newly turned-on Line cards.

Fig. 9b. Number of newly shut-down Line cards.

5.3. Analysis of reroutings

We plot Fig. 10 to show the percentage of traffic which is rerouted in virtual topology by the three different reconfiguration schemes respectively when the traffic load varies from one time period to another during the day. The Full-constrained Reconfiguration causes zero rerouting since we constrained the reroutings of traffic flows to be zero by the Eqs. (12)–(14). The Virtual-Topology-Constrained Reconfiguration causes fewer reroutings than the Unconstrained Reconfiguration in each time period, which means that subset-constraints of lightpaths and line cards for Virtual-Topology-Constrained Reconfiguration are able to reduce some number of reroutings. In addition, the results in Fig. 10 also show that the lower is the traffic load, the higher is the percentage of traffic needed to be rerouted. The reason is that the absolute number of reroutings is similar in each time period, so the percentage of rerouting of traffic is larger when the traffic load is lower.
Based on the analysis of energy consumption, line-card and lightpath reconfiguration and rerouting, three schemes have their different advantages and deficiencies. In summary, the Unconstrained Reconfiguration obtains best amount of energy savings, but largest number of reroutings and reconfigurations; the Virtual-Topology-Constrained Reconfiguration causes fewer reroutings and reconfigurations than Unconstrained Reconfigurations, and cost almost the same energy of Unconstrained Reconfiguration. The Full-Constrained Reconfiguration eliminates the reroutings, but costs a 22.36% higher amount of energy consumption. The network operators are able to make their best choice among these three approaches based on their requirements and practical network scenario.

6. Conclusion and further discussion

Energy consumption of ICT has been gaining increasing concern in recent years. In IP-over-WDM networks, IP routers in the electrical layer and OXCs in the optical layer both consume energy. In this paper, we considered saving energy at both layers by exploiting the opportunities due to traffic variation during the time of the day. We proposed a novel scheme to save energy in IP-over-WDM networks by shutting down idle line cards and chassis of IP routers based on the traffic profile during various times of the day. Based on a realistic case study, about 30% energy savings can be achieved by our scheme. Our scheme also minimizes the potential traffic interruption by minimizing the amount of reconfiguration of network equipments when network elements are being shut down. Results also show that the energy consumption of chassis is dominant compared to the energy consumption of line cards in routers. Therefore, an effective energy-saving scheme should also consider shutting down of entire chassis together with line cards. Besides, all-optical OXCs consume much less energy than the routers in the IP layer in IP-over-WDM networks. The reroutings and potential traffic disruptions are addressed in our paper. We compare the performance of energy consumption and rerouting among three proposed schemes.

This paper deals with a static network planning problem. It is intended to be run off-line based on the predicted traffic variation during the time of the day. We assume the network is in monitored. If traffic exceeds certain limits and other lightpaths should be provisioned, we can use a shortest-path approach to dynamically add other lightpaths. In future work, a dynamic on-line traffic engineering approach can be considered other than static network planning problem based on traffic prediction. Also, the duration of each traffic demand can be taken into account. Since the problem complexity is expected to scale relevantly, a new heuristic approach to minimize both the energy consumption and traffic disruptions needs to be considered.

Acknowledgements

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References