# Energy-Minimized Design for IP Over WDM Networks

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***Abstract*—As the Internet expands in reach and capacity, the energy consumption of network equipment increases. To date, the cost of transmission and switching equipment has been considered to be the major barrier to growth of the Internet. But energy consumption rather than cost of the component equipment may eventually become a barrier to continued growth. Research efforts on "greening the Internet" have been initiated in recent years, aiming to develop energy-efficient network architectures and operational strategies so as to reduce the energy consumption of the Internet. The direct benefits of such efforts are to reduce the operational costs in the network and cut the greenhouse footprint of the network. Second, from an engineering point of view, energy efficiency will assist in reducing the thermal issues associated with heat dissipation in large data centers and switching nodes. In the present research, we concentrate on minimizing the energy consumption of an IP over WDM network. We develop efficient approaches ranging from mixed integer linear programming (MILP) models to heuristics. These approaches are based on traditional virtual-topology and traffic grooming designs. The novelty of the framework involves the definition of an energy-oriented model for the IP over WDM network, the incorporation of the physical layer issues such as energy consumption of each component and the layout of optical amplifiers in the design, etc. Extensive optimization and simulation studies indicate that the proposed energy-minimized design can significantly reduce energy consumption of the IP over WDM network, ranging from 25% to 45%. Moreover, the proposed designs can also help equalize the power consumption at each network node. This is useful for real network deployment, in which each node location may be constrained by a limited electricity power supply. Finally, it is also interesting and useful to find that an energy-efficient network design is also a cost-efficient design because of the fact that IP router ports play a dominating role in both energy consumption and network cost in the IP over WDM network.**

***Index Terms*—Green Internet; IP over WDM network; Energy-minimized network design; Lightpath bypass; MILP model.**

## I. INTRODUCTION

The Internet expansion in reach and capacity results in the increase of the energy consumption of the network equipment. Today the cost of transmission and switching equipment is considered one of the major barriers to the growth of the Internet. But energy consumption rather than cost of the component equipment may eventually become a barrier to continued growth. Today the total energy consumption of the Internet is only a small fraction of the total national electricity supply in most countries, e.g., about 1%–2% of the total electricity consumption in the US in 2000 [1] and about 1% of the total electricity consumption in broadband enabled countries with an average access rate on the order of 30 Mb/s [2]. However, as the Internet expands, these percentages will rise. Moreover, the energy consumption of network equipment can often be confined within a few buildings, which raises an important issue of high energy density. There are two key implications of this. First, increased energy consumption of the Internet will increase operational costs in the network and increase the greenhouse footprint of the network. Secondly, from an engineering point of view, increased energy consumption will exacerbate the thermal issues associated with large data centers and switching nodes [3].

A typical network service provider in a middle-size country consumes 3 TWh of electricity per year (note this is the sum of the total energy consumption by the network equipment of the company as well as the equipment purchased by customers for network services). If an energy-efficient network can be designed and energy-efficient operation strategies can be implemented to cut even 1% of the total energy consumption, then this will lead to a significant cost reduction to save about US$5 billion per year given that the

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price of electricity is seventeen cents per kWh. Research has been initiated in recent years for energy saving of the Internet. This effort was called "greening the Internet" [4]. An IEEE 802.3 Energy Efficient Ethernet Study Group was also established in November 2006 [5]. The study group is currently exploring standardization of ideas related to Adaptive Link Rate (ALR) now renamed as Rapid PHY Selection (RPS) to reduce direct energy use of Ethernet links. A consortium called Green Grid was also formed recently seeking to improve energy efficiency in data centers around the globe [3].

The authors of [4] pioneered to raise the issues of energy saving in the Internet. As a positioning paper [4], several promising strategies were suggested from the component level to the network level. In particular, the authors concentrated on how to save energy consumption by enabling routers and switches to sleep when there is low traffic load. Similarly, by employing a proxying Ethernet adapter to enable dormitory networked computers to sleep, the research in [6] focused on energy saving in local area Ethernet networks.

In the present research, we concentrate on minimizing energy (or power) consumption of the backbone IP over WDM network. Although today the backbone network is only consuming a small fraction of the total network energy, the percentage is perceived to significantly increase with the popularity of bandwidth-intensive user applications such as high-definition IPTV. Moreover, because the energy consumption of the backbone network is often confined to a few buildings, energy density within these key locations is also an important issue. Due to these two perspectives, energy minimization of the IP over WDM backbone network is an important research problem. To reduce energy consumption in the IP over WDM network, lightpath bypass in the optical layer is extensively applied because it can reduce the number of required IP router ports. Based on the lightpath bypass concept, we develop a mixed integer linear programming (MILP) optimization model and two simple but efficient heuristics to minimize energy consumption.

The research problem of designing an energy-efficient IP over WDM network is important because electricity power consumption is one of the major operational costs for a network service provider and today energy is becoming more and more a scarce resource. The *energy-oriented* IP over WDM network model and the *energy-minimized* MILP optimization model and heuristics are also novel, in which the physical layer issues such as power consumption of each component and the layout of optical amplifiers, etc., are specifically considered. These issues are not considered in the traditional IP over WDM network designs [7,8].

In addition, the research outputs from extensive optimization and simulation studies are also insightful. It is found that the proposed energy-minimized IP over WDM design with lightpath bypass can significantly reduce energy consumption over the non-bypass design, ranging from 25% to 45%. It is also found that the energy consumption of the IP over WDM network follows an approximately linear relationship with the network traffic demand intensity. Also, it is interesting to see that IP routers are a major power consumer in the IP over WDM network, which uses more than 90% of the total power, while transponders and EDFAs consume much less power to occupy about 7% and 2% of the total power, respectively. As another important advantage, the lightpath bypass design can also equalize the geographic distribution of power consumption, which is helpful to a network that is subject to a maximal electricity supply at each network node. Finally, it is significant to find that an energy-efficient IP over WDM network is also a cost-effective IP over WDM network.

The rest of the paper is structured as follows. Section II briefs the model of the IP over WDM network and the concepts of lightpath bypass and non-bypass. Section III describes the research problem and explains the proposed MILP optimization model. Two heuristics for energy-minimized design are introduced in Section IV. Section V elaborates on the study cases and test networks of this research. We present research results in Section VI, which show energy savings of the minimization designs, power geographic distributions, and cost comparison between energy-minimized design and cost-minimized design.

## II. IP Over WDM Backbone Transport Networks

The IP over WDM network [10,11] is made up of two layers as shown in Fig. 1, including the IP layer and the optical layer. In the IP layer, a core IP router connects to an optical switch node via short-reach interfaces and aggregates data traffic from low-end access routers. The optical layer provides capacity for the communications between IP routers. Optical switch nodes are interconnected with physical fiber links, of which each may contain multiple fibers. Associated with each fiber, a pair of wavelength multiplexers/demultiplexers are deployed to multiplex/demultiplex wavelengths. The core optical switch box can be either an automatically controllable optical cross-connect (OXC) or a dumb optical patch panel. In this study we assume an optical patch panel is used to fulfill the switching functionality.[1] Associated with each wavelength, a pair of transponders are connected for data transmission. Due to the OEO processing capability of

[1]For the next-generation WDM transport networks, large-size all-optical switches (based on, e.g., MEMS) may be employed.

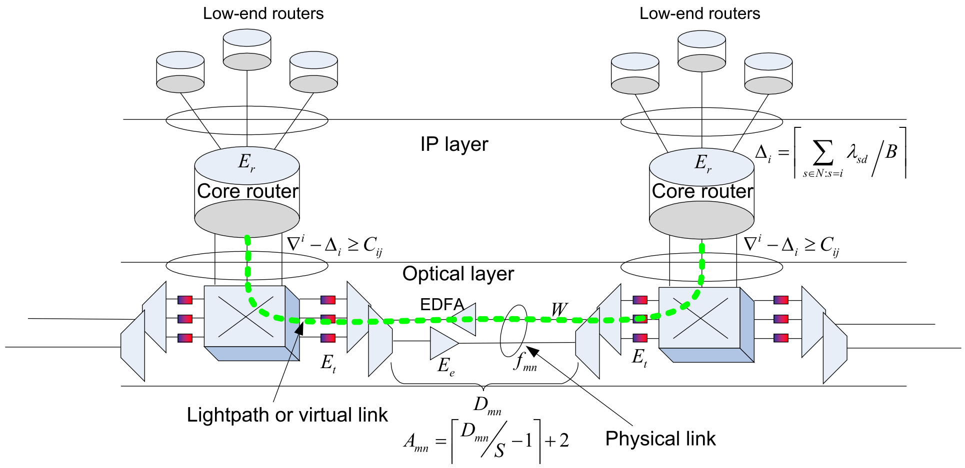


Fig. 1. (Color online) Architecture of an IP over WDM optical network.

each transponder, *full wavelength conversion* can be ensured at the switch node. Finally, to enable optical signals to travel a long distance, EDFA amplifiers are deployed on fiber links.

There are two possible ways to implement IP over WDM networks, i.e., lightpath *non-bypass* and *bypass*. Under lightpath non-bypass, all the lightpaths incident to a node must be terminated, i.e., all the data carried by the lightpaths is processed and forwarded by IP routers. In contrast, the lightpath bypass approach allows IP traffic, whose destination is not the intermediate node, to directly bypass the intermediate router via a cut-through lightpath. Though this requires the optical node to have intelligence to enable lightpath bypass, this can significantly save the total number of IP router ports. The communications between core routers are directly over *lightpaths*, of which each interconnects a pair of router ports. Lightpaths are considered virtual links of the IP layer.

IP routers play a major role in the total energy consumption in an IP over WDM transport network. Thus, minimizing the required number of IP router ports can potentially maximally save the energy consumption of an IP over WDM network.[2] It is well known that the lightpath bypass strategy can help minimize the required IP router ports [7,8]. Thus, this paper focuses on the energy consumption of the IP over WDM network with lightpath bypass. As a performance reference, the energy consumption of the non-bypass design is also provided for comparison.

[2]Based on today's core router architecture [12], generally it is the IP router ports that carry out the IP packet forwarding process, which consumes major energy in the IP router. Thus, it is reasonable and valid to use the number of IP router ports as a measure of the total power consumption of an IP router.

## III. Energy Consumption Minimization Model for IP over WDM Network

### A. Problem Statement

The problem of minimizing energy consumption of an IP over WDM network is stated below. We are given the following inputs to the problem:

1) A physical topology $G_p=(N,E)$, which consists of a set of nodes $N$ and links $E$. The node set corresponds to IP routers and optical switch nodes. Within a single node location, an IP router is connected to an optical switch node by short-reach interfaces. The link set consists of the physical fiber links in the network.
2) A forecast demand matrix $[\lambda]$, which indicates the traffic demand $\lambda^{sd}$ between each node pair $(s,d)$.
3) The number of wavelength channels carried by each fiber $W$ and the capacity of each wavelength $B$ Gb/s.
4) The maximal number of IP router ports at each node $\nabla^i$, which can be a constraint on the problem due to the limited maximal electricity supply at a location.
5) Other given inputs include an average energy consumption of a router port $E_r$, energy consumption of each transponder $E_t$, and energy consumption of each EDFA $E_e$.

All these given inputs are just the parameters of the optimization problem. The objective of the problem is to design an energy-minimized IP over WDM network, subject to the following constraints: 1) serving all the traffic demands, 2) a limited maximal number of wavelengths in each fiber (however, no limit is set on the number of fibers deployed on each physical link), and 3) a limited maximal number of IP router ports at each node.

The problem aims to find 1) an optimal virtual topology in the IP layer, 2) routing of virtual (lightpath) links in the physical layer, and 3) numbers of wavelengths, fibers, and EDFAs required on each physical link.

*B. Other Terms*

We define additional terms as follows:

**Indices:** The following indexing rules are applied for the optimization model:

- $m$ and $n$ — index the nodes in the physical topology $G_p$ (optical layer). A physical link connects two such end nodes.
- $i$ and $j$ — index the nodes in the virtual lightpath topology (IP layer). A lightpath virtual link connects two such end nodes. Physically, the nodes can be a pair of IP routers connected by the virtual link.
- $s$ and $d$ — index source and destination nodes of an end-to-end traffic demand. This demand is aggregated from low-end IP routers and is routed over virtual lightpath topology.

**Sets and parameters:** In addition to all the parameters introduced in Subsection III.A, including $\lambda^{sd}$, $W$, $\nabla^i$, $E_r$, $E_t$, and $E_e$, we define other sets and parameters as follows:

- $N_m$ — set of neighboring nodes of node $m$ in the physical topology $G_p$.
- $L_{mn}$ — physical distance of a physical link between nodes $m$ and $n$. This distance is used to determine the number of required EDFAs on each fiber link.
- $A_{mn}$ — number of EDFAs that should be deployed on each fiber of physical link $(m,n)$. Specifically, $A_{mn}=\lceil L_{mn}/S-1\rceil+2$, where $S$ is the span distance between two neighboring in-line EDFAs and $\lceil L_{mn}/S-1\rceil$ is the number of in-line EDFAs required on the link. "2" counts a post-amplifier and a pre-amplifier respectively at the two ends of a fiber link.
- $\Delta_i$ — number of ports that are used to aggregate the data traffic from the low-end routers at node $i$ (see the interfaces between the core router and low-end routers in Fig. 1), which is computed as $\lceil(\Sigma_{d\in N}\lambda^{id})/B\rceil$.

**Variables:**

- $C_{ij}$ — number of wavelength channels on the virtual link between node pair $(i,j)$ (integer).
- $\lambda_{ij}^{sd}$ — amount of traffic demand between node pair $(s,d)$ that traverses virtual link $(i,j)$ (real).
- $w_{mn}^{ij}$ — number of wavelength channels between node pair $(i,j)$ that traverses physical link $(m,n)$ (integer).
- $w_{mn}$ — number of used wavelength channels on physical link $(m,n)$ (integer).
- $f_{mn}$ — number of fibers on physical link $(m,n)$ (integer).

*C. MILP Optimization Models*

In the literature, MILP models have been developed to minimize either average packet delay or total network costs for the IP over WDM network [7,13,14]. We extended these models for our energy-minimized design. However, it should be clarified that the model developed here differs from the traditional ones in the following aspects:

First, our energy-minimized model concentrates on minimizing total energy consumption contributed by various network components including IP routers, EDFAs, and WDM transponders. In contrast, the traditional virtual-topology design and traffic grooming models generally maximize network throughput or minimize packet delay.

Second, rather than pure network capacity as in the traditional virtual-topology design and traffic grooming models, our energy-minimized model also concerns the physical layer issues such as the layout of EDFAs, the number of required EDFAs related to link wavelength capacity, energy consumption of WDM transponders and EDFAs, etc.

Third, in our energy-minimized model, in addition to the IP router ports used for establishing virtual lightpath links, the ports used for aggregating data traffic from the low-end routers are considered. In contrast, in the traditional models, only IP router ports (or optical transceivers) used for establishing virtual lightpath links between optical cross-connect node pairs are considered.

Mathematically, our energy-minimized design model is as follows:

**Objective:** minimize

$$\sum_{i\in N} E_r\cdot\left(\Delta_i+\sum_{j\in N:i\neq j} C_{ij}\right)+\sum_{m\in N}\sum_{n\in N_m} E_t\cdot w_{mn} + \sum_{m\in N}\sum_{n\in N_m} E_e\cdot A_{mn}\cdot f_{mn} \tag{1}$$

**Subject to:**

$$\sum_{j\in N:i\neq j}\lambda_{ij}^{sd}-\sum_{j\in N:i\neq j}\lambda_{ji}^{sd}=\begin{cases}\lambda^{sd} & i=s\\ -\lambda^{sd} & i=d\\ 0 & \text{otherwise}\end{cases} \quad \forall s,d,i\in N:s\neq d, \tag{2}$$

$$\sum_{s\in N}\sum_{d\in N:s\neq d}\lambda_{ij}^{sd}\leqslant C_{ij}\cdot B \quad \forall i,j\in N:i\neq j, \tag{3}$$

$$\sum_{j \in N: i \neq j} C_{ij} + \Delta_i \leq \nabla^i \quad \forall\, i \in N, \tag{4}$$

$$\sum_{i \in N: i \neq j} C_{ij} + \Delta_j \leq \nabla^j \quad \forall\, j \in N, \tag{5}$$

$$\sum_{n \in N_m} w_{mn}^{ij} - \sum_{n \in N_m} w_{nm}^{ij} = \begin{cases} C_{ij} & m = i \\ -C_{ij} & m = j \\ 0 & \text{otherwise} \end{cases}$$

$$\forall\, i,j,m \in N: i \neq j, \tag{6}$$

$$\sum_{i \in N} \sum_{j \in N: i \neq j} w_{mn}^{ij} \leq W \cdot f_{mn} \quad \forall\, m \in N, n \in N_m. \tag{7}$$

The objective (1) aims to minimize the total energy consumption in both IP and optical layers. The term $\Sigma_{i \in N} E_r \cdot (\Delta_i + \Sigma_{j \in N: i \neq j} C_{ij})$ computes the total energy consumption of routers (in the IP layer) including the ports aggregating data traffic from low-end routers $\Delta_i$ and the ports connected to optical nodes that is the sum of all virtual (lightpath) link capacity $\Sigma_{j \in N} C_{ij}$. The term $\Sigma_{m \in N} \Sigma_{n \in N_m} E_t \cdot w_{mn}$ evaluates the energy consumption of all the transponders in the optical layer, and the term $\Sigma_{m \in N} \Sigma_{n \in N_m} E_e \cdot A_{mn} \cdot f_{mn}$ evaluates the total energy consumption of the EDFA in the optical layer.

Constraint (2) ensures the flow conservation constraint in the IP layer, in which IP traffic between a pair of routers is allowed to be split and transmitted over multiple flow paths. On these flow paths, each capacity link is a virtual lightpath link with $C_{ij} \cdot B$ Gb/s total capacity. Constraint (3) says that each virtual lightpath link has sufficient wavelength capacity allocated to accommodate all the IP flows that traverse the link. The term $\Sigma_{s \in N} \Sigma_{d \in N: s \neq d} \lambda_{ij}^{sd}$ represents the total amount of IP flows that are routed over virtual link $(i,j)$. Constraints (4) and (5) ensure that the total number of deployed router ports at each node never exceeds an upper limit $\nabla^i$, which can be constrained by the maximal electricity supply at the node. Constraint (6) says the flow conservation constraint in the optical layer. Constraint (7) ensures that sufficient wavelength capacity deployed on each physical link to accommodate all the virtual (lightpath) links that traverse it.

Although the above MILP model has been developed to minimize the total energy consumption of an IP over WDM network, it also minimizes the total number of network components, including IP router ports, EDFAs, and transponders, weighted by a set of factors of energy consumption. Thus, if the weighting factors are changed into the costs of network components, the above optimization model can also be used to design a cost-minimized IP over WDM network. Thus, from this point, minimizing the total energy consumption and the total network cost of an IP over WDM network are essentially unified. Later we will show how the total network costs of an energy-minimized design and a cost-minimized design are close to each other.

In computation complexity, the above optimization model has a total of $O(N^4)$ variables and $O(N^3)$ constraints. For a large $N$, there are huge numbers of variables and constraints. For example, if $N=100$, there are a total of about $10^8$ variables and $10^6$ constraints, which makes the problem intractable. Thus, for large-size networks, efficient heuristics are required for fast solution. Next, we will present two simple but effective heuristics for the problem.

## IV. Heuristic Approaches

Based on the lightpath bypass strategy, two heuristics are proposed. The heuristics are extended from single-hop and multi-hop grooming strategies [8,9] in the traditional traffic grooming research. Specifically, the first one is to (simply) directly establish virtual (lightpath) links, whose capacity is sufficient to accommodate all the traffic demands between each node pair (as long as there are traffic demands between them). In the optical layer, the routing of the virtual (lightpath) links is simply based on the shortest path routing algorithm, which can minimize the total number of required transponders and EDFAs given a certain lightpath demand matrix. We term such a scheme "direct bypass." The advantage of this heuristic is its intuition and simplicity, but the disadvantage is that a virtual link must be established no matter how much traffic demand is required between a pair of nodes, so long as there is any. This may lead to low capacity utilization under some circumstances. For example, if a node pair has only 1 Gb/s traffic demand, to serve this traffic demand, a lightpath link with say 40 Gb/s capacity is still required to be set up. Obviously, the utilization of this virtual link will be extremely low, only 2.5%.

To overcome the above drawback, the second approach allows traffic demands between different node pairs to share capacity on common virtual (lightpath) links in order to improve capacity utilization. Although such an effort may elongate the traversing lengths of some (but not many) traffic flows, and turn out to waste network capacity, the overall improvement of network capacity utilization will be more than the waste due to longer IP traffic flows. Better wavelength capacity utilization corresponds to requiring fewer lightpath virtual links for the same traffic demand intensity, and in turn, fewer IP router ports and less energy consumption. Thus, this heuristic is expected to consume less energy than the first "direct bypass" heuristic. We term this heuristic "multi-hop

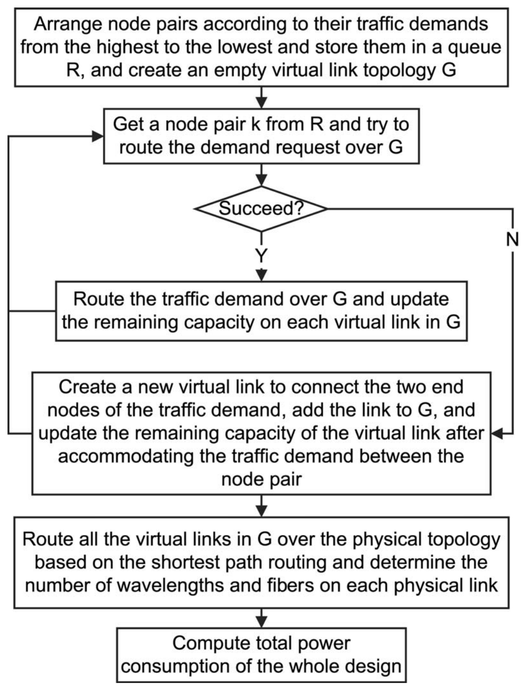


Fig. 2. Flowchart of the multi-hop bypass approach.

bypass." The basic idea of this heuristic is similar to the Maximizing Single-Hop Traffic (MST) algorithm in [8]. The flowchart of the heuristic is shown in Fig. 2.

The algorithm begins with ordering all the node pairs based on their traffic demands from the highest to the lowest amount, and creates an empty virtual topology $G$ that is used to record all the virtual links (i.e., lightpaths in the optical layer) to be established in the subsequent steps. Then it retrieves a node pair from the ordered list, and routes the traffic demand of the node pair over virtual topology $G$. If the virtual topology has sufficient free capacity to accommodate the request, then the algorithm accommodates it and updates the remaining capacity on all the virtual links traversed by the served request. Otherwise, a new direct virtual link is established between the node pair and sufficient wavelength capacity is allocated to the link to accommodate the traffic demand between the node pair. The new link is added to the virtual topology $G$, and the capacity remaining on the link is updated. The above demand request serving process is repeated until all the traffic demand requests in the list are served. Then we route all the virtual links in $G$ over the physical topology in the optical layer. Each virtual link is essentially a lightpath in the optical layer. Once all the lightpaths are routed, we can compute the total energy consumption of the network. In the IP layer, we evaluate the energy consumption of IP routers, which is summed as $\sum_{i\in N} E_r \cdot (\Delta_i + \sum_{j\in N} C_{ij})$, where $\sum_{j\in N} C_{ij}$ counts how many wavelength units starting from node $i$ in virtual topology $G$. Similarly, we can compute the total energy consumption in the optical layer as $\sum_{m\in N}\sum_{n\in N_m} E_t \cdot w_{mn} + \sum_{m\in N}\sum_{n\in N_m} E_e \cdot A_{mn} \cdot f_{mn}$. The computation complexities of the above two heuristics are both on the order of $O(N^4)$. They can both design large-size networks (with hundreds of nodes) within short times.

## V. Study Cases and Test Networks

To evaluate the performance of the above design approaches, we considered five study cases, which include: 1) linear relaxation of the MILP optimization (LP relaxation, in short), 2) MILP optimal design, 3) point-to-point WDM network without lightpath bypass (*non-bypass*, in short), 4) direct lightpath bypass (*direct bypass*, in short), and 5) multi-hop lightpath bypass (*multi-hop bypass*, in short).

Case 1 is a special case of the MILP optimization model with the relaxation of all the integer variables to real variables. The case provides a lower bound on the total energy consumption for the other cases. Case 2 employs the MILP optimization model from Eq. (1) to (7) to obtain an optimal solution, which functions as a reference of how best we can achieve through the heuristic designs. We use the AMPL/CPLEX software package (version 10.1) to solve the MILP problem on a desktop with 3.39 GHz CPU and 1 G memory. Case 3 evaluates the energy consumption of IP over WDM networks if no lightpath bypass is allowed. Specifically, under this design, flow integrity is assumed and all the traffic flows between node pairs follow shortest path routing. After all the traffic demands are served, the case determines how many wavelengths and fibers are required on each physical link and then the total energy consumption. Finally, Cases 4 and 5 are the two lightpath bypass heuristics proposed in Section IV, respectively.

Three test networks were considered, including 1) a six-node eight-link network (n6s8), 2) the 15-node 21-link NSFNET network, and 3) a 24-node 43-link USA backbone IP network (USNET, in short), as shown in Fig. 3. By each link, the physical distance (km) of the link is indicated. In addition, the following inputs were assumed:

1) The traffic demand between each node pair is random with a uniform distribution within a certain range, which is centered at an identical average. That is, given an average demand intensity $X \in \{20, 40, \ldots, 120\}$ Gb/s, the actual demand between a node pair is generated by a random function uniformly distributed within the range $[10, 2X-10]$ Gb/s.
2) The physical distance between two neighboring in-line EDFA amplifiers is assumed to be 80 km, and for any fiber link, by default there are always a pair of post- and pre-EDFA amplifiers respectively at the two ends of the link.

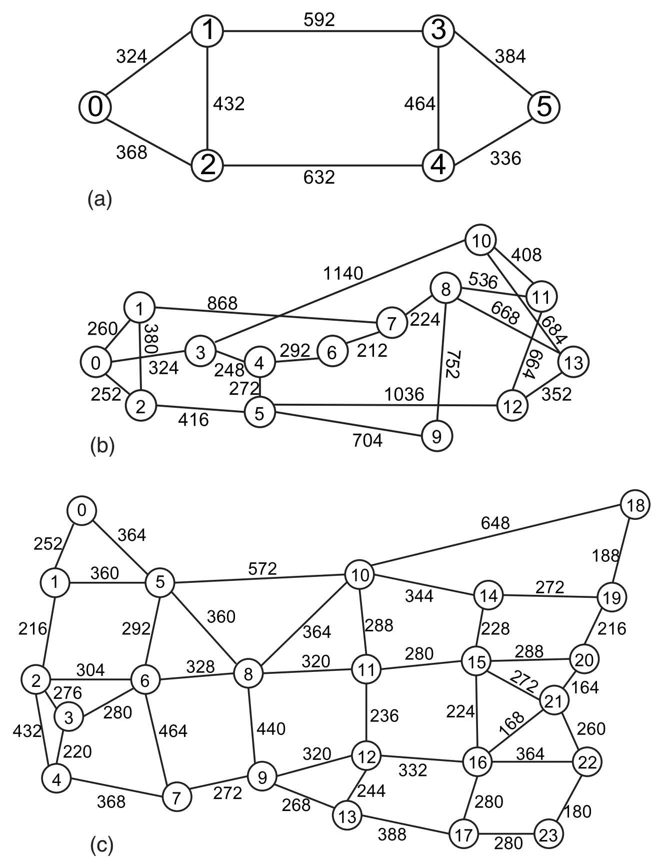


Fig. 3. Test networks.

3) Maximally 16 wavelengths are multiplexed in each fiber, and there is no limit on the total number of fibers on each physical link. The transmission capacity of each wavelength is 40 Gb/s.
4) The energy consumption of each router port is on average 1000 W based on the Cisco 8-slot CRS-1 router data sheet;[3] each WDM transponder is 73 W based on Alcatel-Lucent WaveStar OLS 1.6T ultra-long-haul systems [15], and of each EDFA is 8 W based on Cisco ONS 15501 EDFAs [16]. We show all the input data in Table I.
5) For the n6s8 test network, the constraint of maximal number of IP router ports at each node was set to be 32 in the MILP optimization model. For all the other test scenarios, no such a constraint was assumed.

## VI. Results and Comparisons

### A. Total Power Consumption

Figure 4(a) shows the results of total power consumption of the n6s8 network. The curve "non-bypass" provides an upper bound on the total power

[3]The data was indirectly derived from Cisco's 8-slot CRS-1 data sheets [12]. Each 8-slot CRS-1 chassis consumes about 8 kW of power, so on average each router port consumes about 1 kW of power.

TABLE I
Input Data for the Study

| | |
|---|---|
| Distance between two neighboring in-line EDFAs | 80 km |
| Number of wavelengths in each fiber ($W$) | 16 |
| Transmission capacity of each wavelength ($B$) | 40 Gb/s |
| Average power consumption per IP router port ($E_r$) | 1000 W |
| Power consumption per transponder ($E_t$) | 73 W |
| Power consumption per EDFA ($E_e$) | 8 W |

consumption and the curve "LP relaxation" provides a lower bound on the total power consumption. To ascertain how the lightpath bypass strategy can help to save the power consumption of the IP over WDM network, the curves of power saving of all the lightpath bypass designs relative to the non-bypass design are also shown in Fig. 5(a). By applying the strategy of lightpath bypass, we can maximally save power consumption from 12.5 kW (i.e., 23.5%) to 58.2 kW (i.e.,

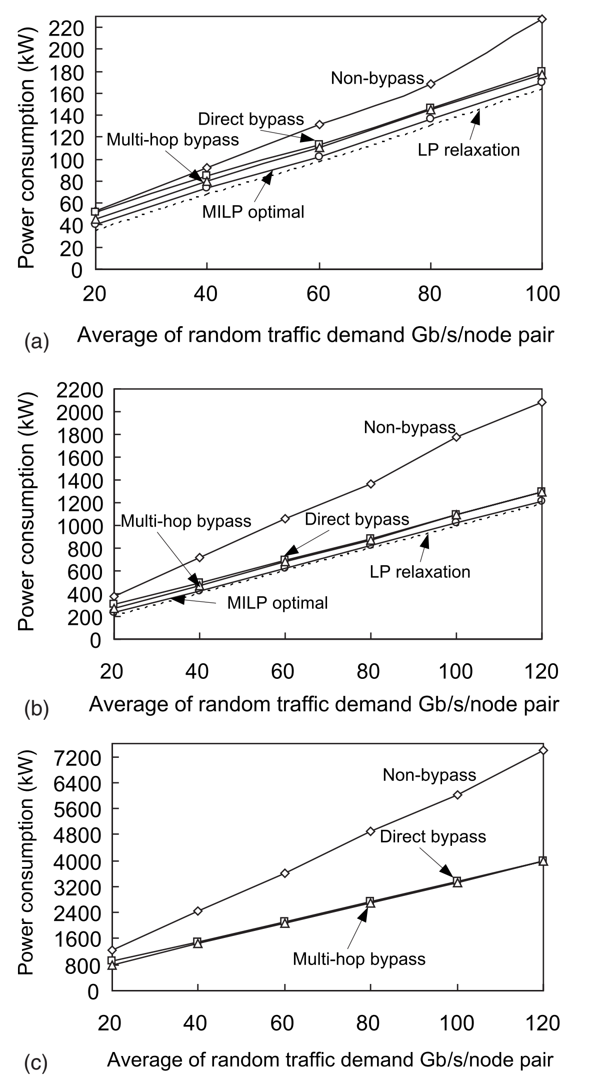


Fig. 4. Comparison of total power consumption between different design approaches.

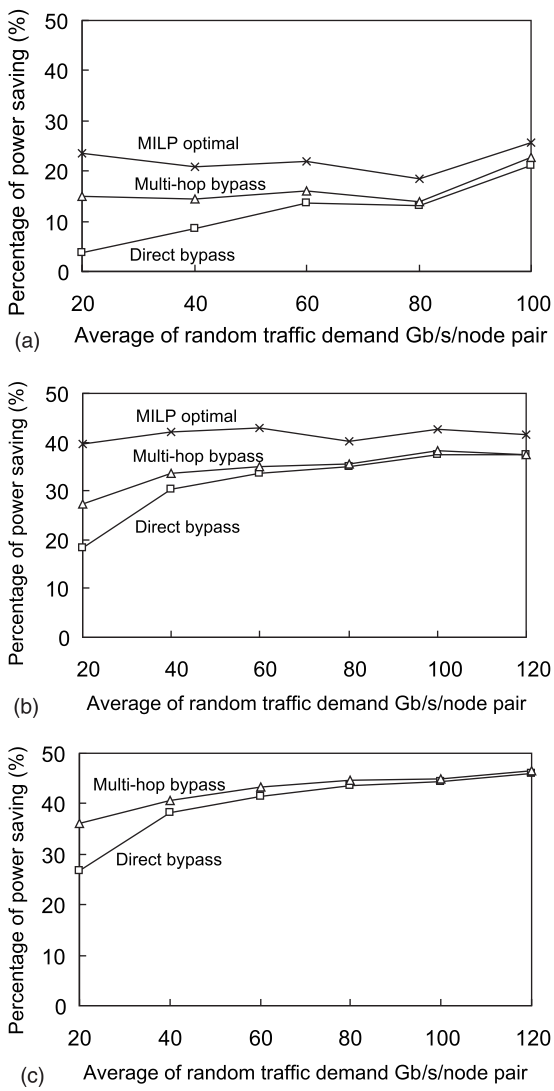


Fig. 5. Power consumption saving by various lightpath bypass approaches relative to the approach of non-bypass.

25.5%) under the MILP optimization design, when the average traffic demand per node pair is increased from 20 Gb/s to 100 Gb/s. In addition, the two heuristics (i.e., "direct bypass" and "multi-hop bypass") are found to perform very closely to the MILP optimization, thereby verifying the effectiveness of the two heuristics. Specifically, the power savings of the two heuristics relative to the non-bypass design are up to 48.0 kW (i.e., 21.0%) and 51.6 kW (i.e., 22.6%) respectively, when the traffic demand intensity is 100 Gb/s per node pair.

In addition, comparing the results of the two bypass heuristics, though the difference is trivial, the "multi-hop bypass" heuristic somewhat performs better than the "direct bypass" heuristic (under low traffic demand intensity), owing to the flexibility of the former in aggregating multiple small traffic flows onto a common lightpath virtual link.

Finally, for all the study cases, an approximately linear relationship between total power consumption and total traffic demand intensity can be found, no matter under the lightpath bypass or non-bypass design, which implies that linear scaling of power consumption is possible when the network traffic demand increases.

Similar simulation studies were carried out for the other two large-size networks, NSFNET and USNET. The results of NSFNET are shown in Fig. 4(b) and Fig. 5(b), and the results of USNET are in Fig. 4(c) and Fig. 5(c). All the design cases keep the same ranks in the total power consumption in both of the networks. However, comparing the results of the three different-size networks, an important observation is that with the increase of network size, the power saving by the lightpath bypass strategy increases. The NSFNET network has 40% saving and the USNET network has even more than 45% saving, versus about 25% saving of the smaller n6s8 network. This is explainable because with the increase of network size, there are more chances to establish longer lightpaths, which bypass more intermediate switch nodes and hence require relatively fewer IP router ports.

### *B. Distribution of Component Power Consumption*

In addition to the total power consumption, it is interesting to see the distribution of power consumption by each type of component in the IP over WDM network. Figures 6(a) and 6(b) show this type of distribution for the n6s8 network. The results were obtained based on the MILP optimization design. We can see that IP routers consume the highest percentage (more

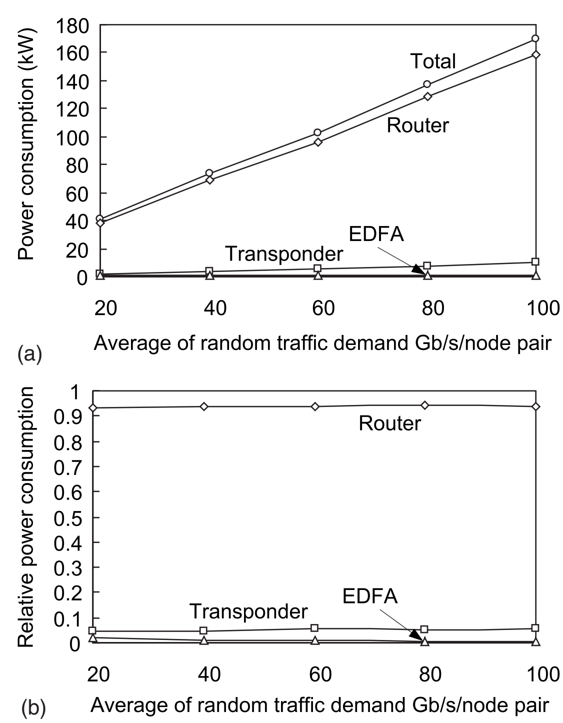


Fig. 6. Power consumption of different types of components in IP over WDM networks (n6s8).

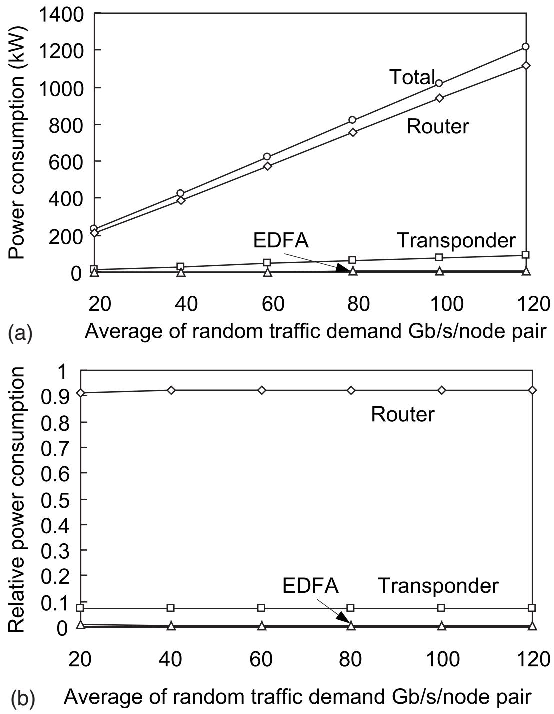


Fig. 7. Power consumption of different types of components in IP over WDM networks (NSFNET).

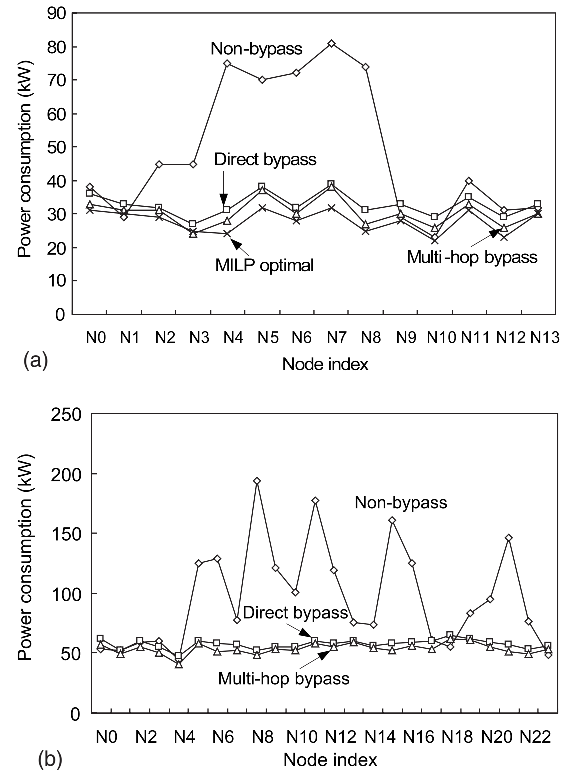


Fig. 8. Power consumption geographic distributions under various designs.

than 90%) of the total power. The remaining energy is shared by transponders and EDFAs, among which transponders occupy about 5% and EDFAs consume $\leqslant 3\%$.

Similar MILP optimization results were obtained for the larger-size NSFNET network. Figures 7(a) and 7(b) show the distribution of power consumption of different types of components. The results are similar to those of the n6s8 network. IP routers consume about 91% of total power, transponders occupy about 7%, and EDFAs consume less than 2%.

### C. Geographic Distribution of Power Consumption

As the network expands, there will be increasing practical problems associated with supplying large amounts of energy to large network nodes and the associated problems in removing the associated heat. Therefore, telcos and ISPs may wish to distribute the power consumption around their network rather than to concentrate it. One simple approach to solving this problem is to evenly distribute the power consumption so that it is similar in all nodes. The optimization designs based on the lightpath bypass strategy can help this.

We consider the geographic distribution of router power consumption.[4] Given an average 40 Gb/s traffic demand per node pair, Fig. 8(a) shows the distribution of power consumption of the nodes in the NSFNET network. It shows that without lightpath bypass, the power consumption distribution has a large variance. Some locations consume more than 80 kW power, while other locations consume as low as 20 kW power, of which the variance is up to 20.0 kW. In contrast, all the lightpath bypass designs show much more uniform power distributions though the traffic demand per node pair is random. In addition to reducing total energy consumption, the bypass design approaches are found to have power distribution variances as low as about 3.5 kW. Similar studies were performed for the other large test network, USNET. The power distributions are shown in Fig. 8(b). In line with the distributions of NSFNET, we find that the lightpath bypass designs always demonstrate more uniform power distributions with variances as small as about 4 kW, while the non-bypass design shows a much larger variance, more than 42.0 kW. To further verify this observation, similar simulations were conducted for a European network topology. The same conclusion was found that the lightpath bypass strategy can help to equalize the power consumption in the network.

[4]Due to the dominating role (more than 90%) of power consumption by IP routers in the whole IP over WDM network, we use the power consumption of IP routers to approximately estimate the total power consumption at each network node.

### D. Energy Versus Cost

Finally, as mentioned in Subsection III.B, the energy-minimized model is versatile enough to enable the design of a cost-minimized network as well if we change the optimization weights of each component in the model from energy consumption to cost. We also evaluated the cost of IP over WDM network design. Specifically, in addition to the network components that have been included in the model from Eq. (1) to (7), we calculated the cost of optical multiplexers and demultiplexers. Note that optical multiplexers and demultiplexers, however, should not be included in the energy consumption model as they are passive optical components. We did not consider the cost of fibers by assuming that there have been many dark fibers deployed between network nodes. Table II shows the cost values used in the study.

For a simple comparison, Fig. 9 shows the costs of energy-minimized and cost-minimized designs for the n6s8 network (based on the MILP optimization model). We can see that though the two designs have different optimization objectives they show almost the same network design costs. This is reasonable because it is found that a network component that consumes more energy (e.g., IP router port) is coincidentally generally more expensive as well. The conclusion is also valid for the larger NSFNET network according to our simulation tests. However, it should be noted that the above conclusion may not be valid if a component with low energy consumption is the most expensive. In that case, the cost difference between an energy-minimized design and a cost-minimized design can be up to 10% for some design cases of NSFNET, depending on how expensive the cost of the low energy-consuming component is relative to the cost of the high energy-consuming component.

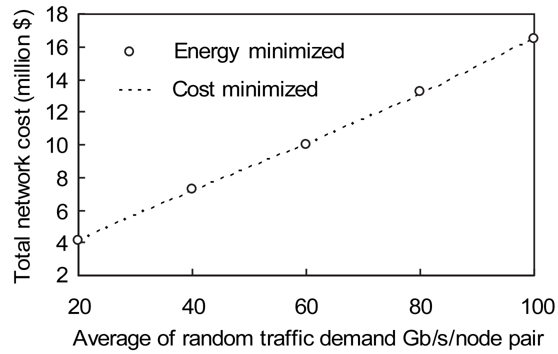


Fig. 9. Network cost comparison between energy-minimized design and cost-minimized design.

## VII. Conclusion

Energy consumption of network equipment may eventually become a barrier for the Internet to further grow. It is important to explore energy-efficient networking techniques for future communication networks. This paper looks into the power saving of the IP over WDM network. To reduce power consumption, we developed an MILP optimization model and efficient heuristics based on the lightpath bypass strategy for the IP over WDM network. It was found that the strategy of lightpath bypass can significantly save power consumption over the non-bypass design, ranging from 25% to 45%. Such saving increases with the increase of network size. It was also found that the energy consumption of the IP over WDM network follows an approximately linear relationship with the network traffic demand. Based on the power consumption of each type of network component, we also found that IP routers are a major power consumer in the IP over WDM network, which uses more than 90% of the total power. The study of power consumption geographic distribution indicated that, in addition to energy saving, the lightpath bypass strategy can equalize the geographic distribution of power consumption, which is important for some situations that are subject to maximal electricity supply at a network node location. In addition, it is meaningful to see that an energy-efficient network design is coincidentally a cost-efficient design due to the fact that IP router ports play a dominating role in both energy consumption and network cost in an IP over WDM network. Finally, the comparison between the designs of the MILP model and the heuristics shows that the heuristics are efficient to perform similarly to the MILP optimization design.

TABLE II
Cost Data for the Study

| | |
|---|---|
| Router (40 Gb/s port) | $80,000 per port |
| 40 Gb/s transponder | $25,000 |
| Optical EDFA | $1,500 |
| Optical multiplexer/demultiplexer | $5,000 |

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