Optimized Design of Energy-Efficient IP Over WDM Networks

F. Mousavi Madani

Faculty of Engineering, Alzahra University,
Tehran, Iran.
e-mail: mosavif@alzahra.ac.ir

Abstract—**A surge of interest toward design and implementation of green networks are emerging in recent years. One obvious trend to reduce energy consumption of major active network components is to craft backbone network architecture that takes into consideration traffic grooming of low-rate IP traffic as well as power-aware virtual topology design schemes and RWA. Previous research efforts developed design strategies which assumed digital processing of incoming traffic flows at ever node structure in the optical layer (DXCs). This architecture provides full wavelength conversion capability by the use of optical transponders (OEO convertors) thus reduces complicated RWA problem to a simple routing problem at the cost of sacrificing lightpath transparency. Moreover, introduction of transponders give rise to extra sources of power consumption which contrasts over goal. In this paper, energy-minimized design of IP over WDM networks based on optical cross connects (OXCs) is investigated. Integer linear programming formulation for two design strategies viz. multi-hop lightpath and direct lightpath have been developed and their performance with regard to power consumption and bandwidth utilization are compared with prior studies. Simulation results indicate superior performance of the proposed multi-hop transparent lightpath strategy.**

Keywords- Energy-minimized design, multi-hop lightpath, direct lightpath.

I.   INTRODUCTION

Growing energy consumption of backbone optical networks has recently aroused global attention toward planning energy efficient networks. With rapid expansion and processing speed of underlying equipment to support next-generation high-speed Internet services and cloud computing has further strengthened the importance of power saving trends. Some researchers proposed power-aware routing and wavelength assignment (PA-RWA) algorithms that takes power consumption of traffic load into routing considerations [1, 2]. For IP over WDM networks, some authors have focused their intention on traffic grooming and optical bypass as green provisioning strategies [3]. Also, sleep mode option for the optical devices (e.g., amplifiers, optical switches) installed for protection purposes have been considered in [4]. These devices can be put in sleep mode to reduce the network power consumption, but they can be promptly waken up (if necessary) upon a failure occurrence.

In this paper, novel MILP formulations for optimization of power consumption in the network design architecture based on optical cross-connect switches (OXCs) and IP core routers have been introduced. The multi-hop transparent model provides simultaneously optimal virtual topology design and RWA to minimize the number of ports in core routers. It supports traffic grooming and full wavelength conversion at intermediate cross-connecting nodes while maintaining optical transparency on each lightpath. The direct lightpath model investigates design of energy minimized single-hop all optical network.

The rest of the paper is organized as follows: section 2 presents schematic of the backbone network. Detail mathematical formulations for design strategies are introduced in section 3. Section 4 provides simulation results and performance comparison among design strategies. Finally, section 5 concludes the paper.

II.   CORE NETWORK MODEL

The architecture shown in Fig. 1 is used for modeling IP over WDM backbone network. Specifically, every node is composed of a core router which collects user's traffic from access routers at the IP layer and connects aggregated traffic streams to optical cross connect (OXC) via short-reach interface. OXCs at the optical layer are interconnected by optical fiber links that carries at most W wavelengths each with a carrying capacity of B Gb/s. For multiplexing/de-multiplexing of wavelength channels at output/input ports of OXC, a pair of optical passive multiplexer/demultiplexer are used for each fiber link. Clearly, the model represents circuit-switched multi-fiber optical network that implements a virtual link at the IP layer with a transparent lightpath at the optical layer. So wavelength conversion is not available in nodes and wavelength continuity should be conserved through whole network. In order to enable optical signals to traverse long distances, EDFA amplifiers are introduced at regular distances.

Also shown in Fig. 1, three major source of energy consumption are network line card of core router (E_r), transponder (E_t) and EDFA (E_e) so total power consumption can be computed from the number and types of router ports, total number of fibers and geographic span of the network. Here, without losing generality, three types of router line cards are considered, namely one-port, two-ports and four-ports line cards. Such a distinction was made based on the presumption that an N-port line card consumes less energy than N one-port line cards.

From the network design perspective, two different strategies can be employed to design IP over WDM networks, namely *multi-hop transparent lightpath bypass* and *direct lightpath bypass* strategies. Under multi-hop bypass strategy, each virtual link at IP layer is mapped onto several

concatenated lightpaths at optical layer. Over each lightpath, all IP traffic passing through an intermediate router are directly bypassed at the corresponding OXC. At the destination node of a virtual link, however, traffic carried by all wavelength channels are dropped and forwarded to core router for electronic processing. This allows traffic grooming at interconnections between virtual links to attain benefits of traffic grooming for improved bandwidth utilization. Such improvement, of course, can be obtained only at the cost of sacrificing full lightpath transparency. In contrast, direct lightpath strategy achieves full wavelength transparency by deploying direct lightpath between every source-destination pair at the cost of missing the benefits of traffic grooming. The performance of these two scenarios in terms of energy consumption and bandwidth utilization will be investigated in later section. We have also included *multi-hop opaque lightpath bypass* scenario discussed in [5] where a combination of O-E-O transponders and DXCs allow for implementation of full wavelength conversion at each node. It relieves wavelength continuity constraint and reduces the complex RWA problem to a simple routing problem. For the sake of benchmarking results with an ideal lower band limit, the LP-relaxed version of the model is taken into consideration.
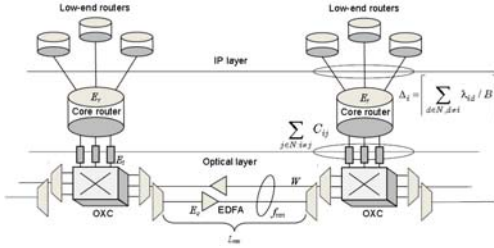

Figure 1. Architecture of IP over WDM network

III. ENERGY-MINIMIZED MATHEMATICAL MODELS

The so-called *multi-hop lightpath bypass* and *direct lightpath bypass* strategies, the problem of designing an IP over WDM network with minimum power consumption can be formulated as a mixed integer linear programming (MILP) model. Our objective is to find energy-minimized design subject to 1) serving all traffic demands, 2) a fixed maximum number of wavelengths per fiber. No limit on the number of fibers in each physical link was set to accommodate required carrying capacity.

Input parameters:
- $G(N, E)$: A physical topology which consists of a set of nodes N and links L. The node set corresponds to network nodes, of which each consists of an IP router and an OXC. The link set consists of physical fiber links in underlying network topology.
- N_m: The set of neighboring nodes of node m in the physical topology.
- T: set of router line card types. We assume three types of one-port, two-port and four-port types of line cards.

- λ^{sd}: Traffic demand between each node pair (s, d). We further assume a symmetric traffic demand matrix, i.e. $\lambda^{sd} = \lambda^{ds}$.
- E_r^k: Power consumption of kth type of router line card.
- E_t: Power consumption of a transponder.
- E_e: Power consumption of an EDFA.
- L_{mn}: Distance between node m and node n in physical topology.
- A_{mn}: The number of EDFAs that should be placed in line on each physical link (m,n). Specifically, $A_{mn} = \lceil L_{mn} / S - 1 \rceil + 2$, where S is the span distance between two adjacent EDFAs (the value of 80 km is common in practice and used in simulations). "2" counts for post- and pre-amplifiers at fiber ends.
- Δ_i: The number of ports used to aggregate low-rate traffic from low-end routers at node i (see figure. 1).
- P_k: The number of ports contained in the kth type of router line card.
- W: Maximum number of wavelengths per fiber.
- B: Bit rate per wavelength channel.

Scenario I: *multi-hop lightpath bypass strategy*
Decision variables:
- λ_{ij}^{sd}: The amount of traffic demand between node pair (s, d) that traverses virtual link (i, j).
- $w_{mn,w}^{ij}$: The amount of traffic flow (number of wavelengths) between node pair (i, j) at wavelength w that traverses physical link (m, n).
- C_w^{ij}: Traffic flow (number of wavelengths) passing through virtual link (i, j) at wavelength w.
- C^{ij}: Total traffic flow passing through virtual link (i, j).
- f_{mn}: Number of fibers on physical link (m, n).
- Y_i^k: Number of kth type of router line cards deployed at node i.

Objective:

$$\text{Minimize} \quad \sum_{i \in N} \sum_{k \in T} E_r^k \cdot Y_i^k + E_t \cdot \sum_{i \in N} \sum_{j \in N : i \neq j} C_{ij} + E_e \cdot \sum_{m \in N} \sum_{n \in N_m} A_{mn} \cdot f_{mn} \quad (1)$$

Subject to:

$$\sum_{k \in T} P_k \cdot Y_i^k \geq \Delta_i + \sum_{j \in N : i \neq j} C_{ij} \qquad \forall i \in N \quad (2)$$

$$\sum_{j \in N : i \neq j} \lambda_{ij}^{sd} - \sum_{j \in N : i \neq j} \lambda_{ji}^{sd} = \begin{cases} \lambda^{sd} & \text{if } i = s \\ -\lambda^{sd} & \text{if } i = d \\ 0 & \text{otherwise} \end{cases} \forall s, d, i \in N : s \neq d \quad (3)$$

$$\sum_{s \in N} \sum_{d \in N : s \neq d} \lambda_{ij}^{sd} \leq C_{ij} \cdot B \qquad \forall i, j \in N : i \neq j \quad (4)$$

$$\sum_{n \in N_m} w^{ij}_{mn,w} - \sum_{n \in N_m} w^{ij}_{nm,w} = \begin{cases} C^{ij}_w & \text{if } m = i \\ -C^{ij}_w & \text{if } m = j \quad \forall i,j,m \in N, \\ 0 & otherwise \quad w \in W : i \neq j \end{cases} \quad (5)$$

$$\sum_{i \in N} \sum_{j \in N : i \neq j} w^{ij}_{mn,w} \leq f_{mn} \qquad \forall m \in N, n \in N_m, w \in W \quad (6)$$

$$\sum_{w \in W} C^{ij}_w = C^{ij} \qquad \forall i, j \in N : i \neq j \quad (7)$$

Objective (1) is defined to minimize the overall network power consumption. The first term computes total power consumption by IP routers. The second term sums up power consumption of all transponders connected to OXCs and the last term calculates total power consumption of pre-, post- and inline optical amplifiers.

Constraint (2) ensures that router line cards at each node have sufficient ports to accommodate IP traffic. Constraint (3) reflects traffic flow conservation at each node. Constraint (4) is included to dedicate enough virtual link capacity to support all traffic demands that use the link. Constraint (5) maintains flow conservation and wavelength continuity over a lightpath at optical layer. Constraint (6) prevents from wavelength channel collision at every fiber link. Finally, constraint (7) counts total amount of traffic flow over each virtual link.

Scenario II: *direct lightpath bypass strategy*
Decision variables:

- C^{sd} : Number of wavelength channels between node pair (s, d) that carry traffic demand λ^{sd}.

- C^{sd}_w : Number of wavelength channels between node pair (s, d) on wavelength w.

- $C^{sd}_{mn,w}$: Number of wavelength channels between node pair (s, d) on wavelength w that traverses physical link (m, n).

- f_{mn} : Number of fibers on physical link (m, n).

- Y^k_i : Number of kth type of router line cards deployed at node i.

Objective:

Minimize

$$\sum_{i \in N} \sum_{k \in T} E^k_r \cdot Y^k_i + E_t \cdot \sum_{s \in N} \sum_{d \in N : s \neq d} C^{sd} + E_e \cdot \sum_{m \in N} \sum_{n \in N_m} A_{mn} \cdot f_{mn}$$

$$(8)$$

Subject to:

$$\sum_{k \in T} P_k \cdot Y^k_i \geq \Delta_i + \sum_{j \in N : i \neq j} C^{ij} \qquad \forall i \in N \quad (9)$$

$$\lambda^{sd} \leq C^{sd} \cdot B \qquad \forall s, d \in N : s \neq d \quad (10)$$

$$\sum_{n \in N_m} C^{sd}_{mn,w} - \sum_{n \in N_m} C^{sd}_{nm,w} = \begin{cases} C^{sd}_w & \text{if } m = s \\ -C^{sd}_w & \text{if } m = d \quad \forall s,d,m \in N, \\ 0 & otherwise \quad w \in W : s \neq d \end{cases} \quad (11)$$

$$\sum_{s \in N} \sum_{d \in N : s \neq d} C^{sd}_{mn,w} \leq f_{mn} \qquad \forall m \in N, n \in N_m, w \in W \quad (12)$$

$$\sum_{w \in W} C^{sd}_w = C^{sd} \qquad \forall s, d \in N : s \neq d \quad (13)$$

Constraint (9) is similar to constrain (2). Constraint (10) is included to dedicate enough wavelength capacity at every node to support all traffic demands of that node. Constraint (11) maintains wavelength flow conservation and continuity over a lightpath between a pair of source-destination node. Constraint (12) prevents from wavelength channel collision at every fiber link. Finally, constraint (13) counts total number of wavelengths between an (s, d) pair.

IV. SIMULATION RESULTS

To evaluate the performance of the fore mentioned design scenarios, two test networks were considered as shown in figure 2. The first one is conventionally chosen as a typical topology referred in many papers. The second one is a 15-node 21-link NSFNET network. The physical length of every link is indicated just close to it in kilometers unit. Additionally, the following inputs were supplied:
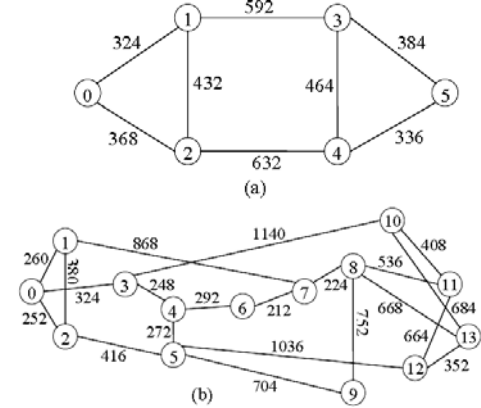

Figure 2.   Test networks

1) The traffic demand between each pair of nodes was randomly generated with uniform distribution over the range [0, 2X] Gb/s where the average demand was taken from a set of presumed values $X \in \{20, 40, ..., 140\}$.

2) The maximum number of wavelength channels in each fiber is taken from the set $W \in \{2, 4, 8, 16\}$ depending on the purpose of study and transmission capacity of each wavelength channel is 40 Gb/s.

3) The energy consumption of each type of router line card is taken from [6] to be: L_TYPE1 = 1000 W, L_TYPE2 = 1800 W, and L_TYPE4 = 3400 W. Moreover,

according to [6] each WDM transponder consumes 73 W, and each EDFA consumes 8 W.

Figure 3(a) shows the variation of minimum power consumption of n6s8 network versus average traffic intensity for different design strategies when the maximum number of wavelengths per fiber is set to 4. Figure 3(b) depicts the same plot for the NSFNET network. In both cases we notice better energy performance of the proposed transparent multi-hop lightpath bypass design compared to
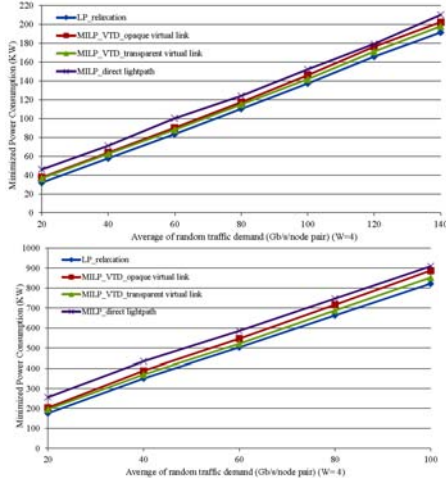

Figure 3. Comparison of total power consumption of different design strategies (a) n6s8 network, (b) NSFNET network.

the reference model of opaque multi-hop lightpath bypass. Energy saving is higher for heavy loads and as expected mainly stems from significant reduction in the number of transponders for passing by channels due to the replacement of DXC with OXC. Upper bound corresponds to direct lightpath bypass strategy since it requires more wavelength channels at each node for a given traffic demand owing to the lack of traffic grooming capability and wavelength continuity constraint. As a result higher number of IP router ports and inline amplifiers (due to the scarcity of available wavelengths to route a lightpath thus imposing an increase in fiber strands) translates into poor energy performance.
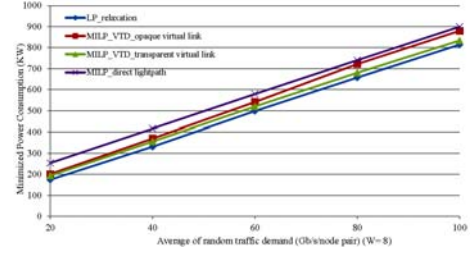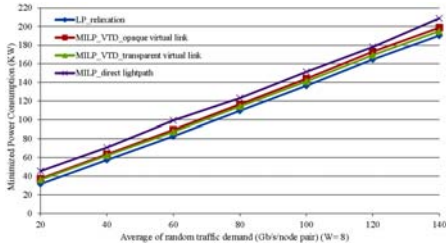

Figure 4. Comparison of total power consumption of different design strategies (a) n6s8 network, (b) NSFNET network.

The price we should pay for obtaining full wavelength transparency exacerbates at large networks with low to moderate traffic loads with up to about 40% increase in overall power consumption.

Figure 4(a) and (b) plots the same results for the case of a maximum number of 8 wavelengths per fiber. The improvement in the performance of our proposed approach (MILP_VTD_transparent) compared with the reference model (MILP_VTD_opaque) is higher for NSFNET than n6s8 network in case of moderate to high average traffic demands for both $W = 4$ and $W = 8$. Such behavior can be attributed to longer lightpath routes associated with each virtual link in a large backbone network which brings forth enhanced benefit of replacing DXC with OXC. For larger networks, close to ideal energy consumption of the proposed strategy, regardless of the number of provisioned wavelengths in a fiber strand and the amount of traffic demands, may be concluded subsequently.

V. CONCLUDING REMARKS

Design of green optical networks have recently attracted enormous research attitude due to rapid expansion and exclusive role of these network as the backbone of next generation Internet. In this paper two design strategies to deploy IP over WDM optical network based on optical cross-connect switches were introduced and mathematical models to optimize their energy consumption performance were developed. Energy consumptions for different traffic loads were compared with those of a similar model where digital cross-connect switches were employed instead. Simulation results showed that our proposed multi-hop transparent lightpath bypass approach achieve better energy performance than the opaque lightpath bypass design under the same traffic loads. Direct lightpath bypass design approach (fully transparent single-hop) could also achieve very close performance to the optimal scenario.

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