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Energy Efficient Design Strategies of Translucent and Transparent IP Over WDM Networks

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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 every 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 as well as heuristics for two design strategies viz. multi-hop lightpath and direct bypass have been developed and their performance with regard to power consumption and relative bandwidth utilization are compared. Simulation results indicate superior performance of the proposed strategies with regard to previous studies.**

Keywords-***component; 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 translucent 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 bypass model investigates design of energy minimized single-hop all optical network.

We further developed energy-minimized oriented heuristics for the fore mentioned design scenarios to overcome processing burden of pure mathematical models.

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 heuristics as near optimal solution. Section 5 represents simulation results and performance comparison among design strategies for three test networks. 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, *multi-hop transparent lightpath bypass* (namely *translucent*) 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.

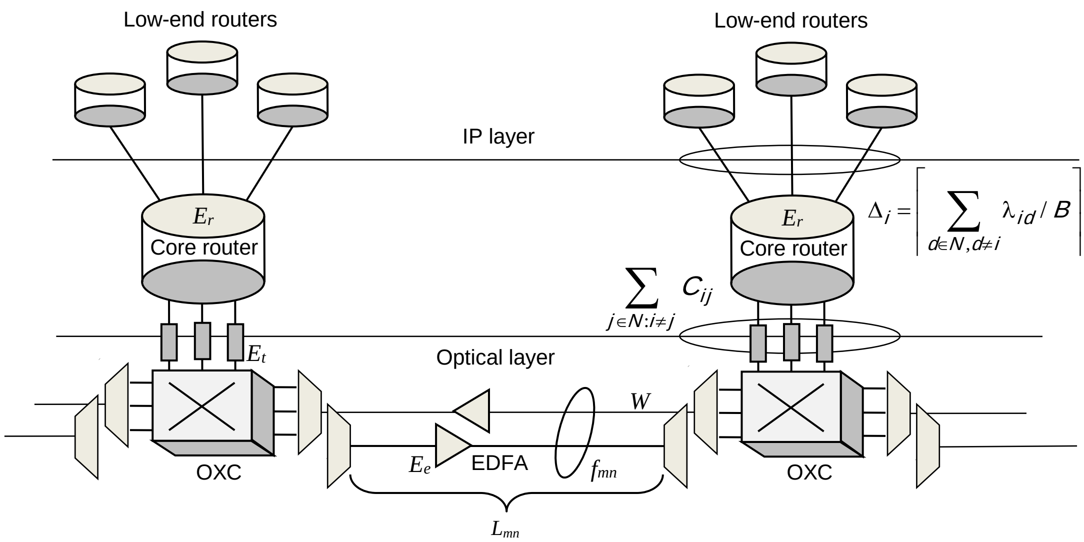


Fig. 1. Architecture of IP over WDM network

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 relative BW utilization will be contrasted in the 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 and upper band limits, the LP-relaxed version of the model and Non-bypass design schemes are taken into consideration, respectively.

III. Energy-Minimized Mathematical Models

In 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 k^th 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 k^th 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 k^th type of router line cards deployed at node i.

Objective:

Minimize

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

Subject to:

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

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

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

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

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

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

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 k[th] type of router line cards deployed at node i.

Objective:

Minimize

$$\sum_{i\in N}\sum_{k\in T} E^{k}_{r}\cdot Y^{k}_{i} + E_t\cdot\sum_{s\in N}\sum_{d\in N:s\neq d} C^{sd} + E_e\cdot\sum_{m\in N}\sum_{n\in N_m} A_{mn}\cdot f_{mn} \quad (8)$$

Subject to:

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

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

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

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

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

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. HEURISTIC ALGORITHMS

The preceding ILP formulation becomes computationally intractable even for medium-sized networks when fiber channel capacity grows beyond 4 ~ 8 wavelengths. Heuristic algorithms have been extensively studied to tackle VTD and RWA optimization problems. For the case in hand, two heuristics corresponding to the above design schemes were developed toward minimizing energy consuming components. Flowchart of the multi-hop bypass design scheme is shown in Fig. 2. First, the sub-wavelength part of every traffic demand is extracted and stored for traffic grooming in the latter stage. Since wavelength granular part of every demand pair cannot be aggregated with other traffic demands, we try to carry it in a single-hop direct lightpath fashion in the first round. This proceeds as an attempt to eliminate intermediate optical regenerators thereby minimizing router line cards which are the major energy consuming components. The RWA heuristic was constructed based on k-shortest path routing combined with First-Fit wavelength assignment in an effort to minimize both number of inline amplifiers as well as required number of fibers per physical link for a given *W*. The next round was crafted to exploit benefit of traffic grooming capability over multi-hop virtual links. For each remaining sub-wavelength traffic demand, it tries to find virtual path with minimum maximal traffic load to enhance load balancing thus improving resource utilization. As the new traffic pattern was developed after the completion of VTD design stage, RWA heuristic is invoked again to decide optimal physical resource allocation. The devised algorithm works for direct bypass strategy as well where whole traffic demand volume of every node pair is completely processed in the first round without any concern to other demands. So every request was implemented as multiple direct lightpaths over a single virtual ink.

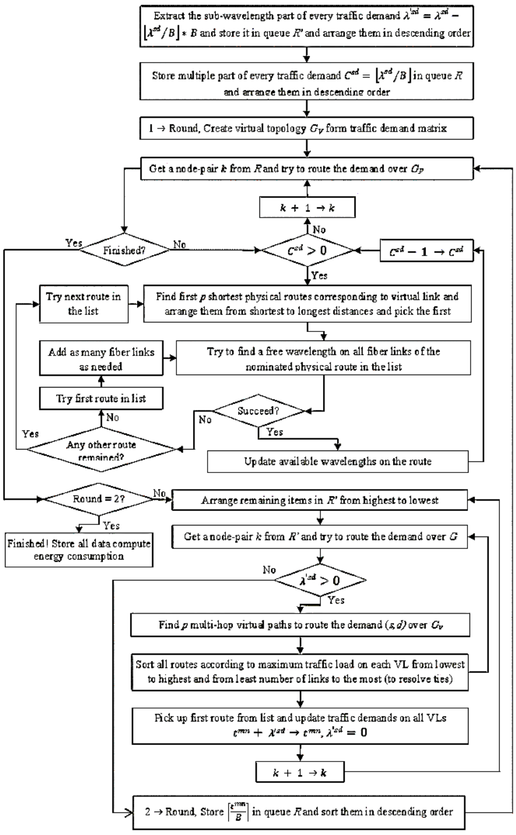


Fig. 2. Flowchart of translucent design scheme

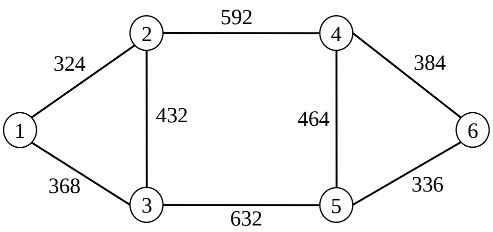
V. SIMULATION RESULTS

To evaluate the performance of the fore mentioned design scenarios, three test networks were considered as shown in Fig. 3. 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 and the third one is 24-node 43-link USA backbone IP network (USNET in short). The physical length of every link is indicated just close to it in kilometers unit. Additionally, the following inputs were supplied to the model:

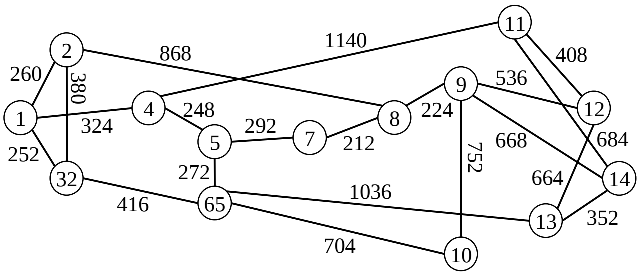
1) The traffic demand between each pair of nodes was randomly generated with uniform distribution over the range [0, 2X] Gb/s where the average demand was taken from preset values $X \in \{20, 40, ..., 140\}$.

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.

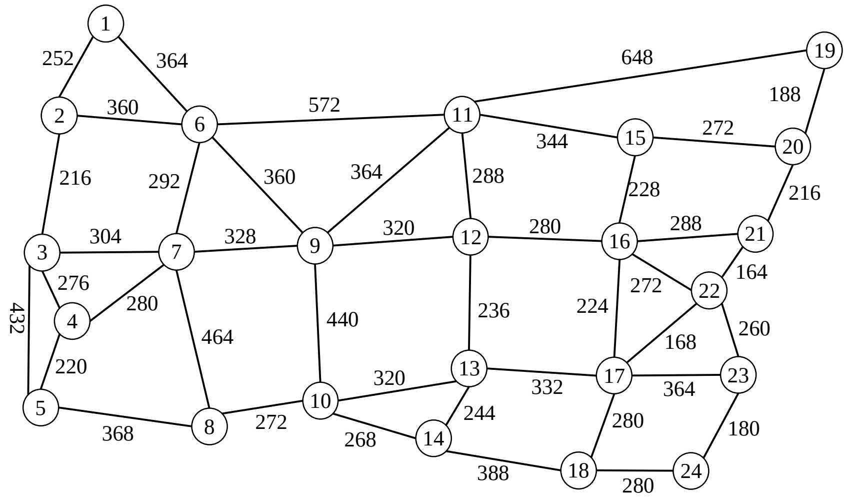
3) The energy consumption of each type of router line card is taken from [6] to be: L_TYPE1 = 580 W, L_TYPE2 = 1000 W, and L_TYPE4 = 2000 W. Moreover, according to [7] each WDM transponder consumes around 70 W, and each EDFA consumes 10 W.



(a) n6s8



(b) NSFNET



(c) USNET

Fig. 3. Test networks

Fig. 4(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 8. Fig. 4(b) and (c) depict the same plot for the NSFNET and USNET networks respectively. In the first two cases we notice better energy performance of the proposed multi-hop translucent design compared to the reference opaque multi-hop lightpath bypass model. Energy saving is slightly 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. However, in considering bandwidth utilization of these two schemes, it may be postulated that higher resource requirements for maintaining transparency in the translucent design scheme leads inevitably to sacrifice in BW utilization. Relative BW utilization of test networks for different average traffic loads are illustrated in Fig. 5 (a) to (c). For each case, the BW utilization of single-channel direct-bypass network was taken as a reference and was calculated as ratio of overall network throughput to total wavelength capacity. Apparently, in both n6s8 and NSFNET networks, relative BW utilization of the proposed multi-hop translucent design shows almost the same quantity or even better than the opaque design for all traffic loads.

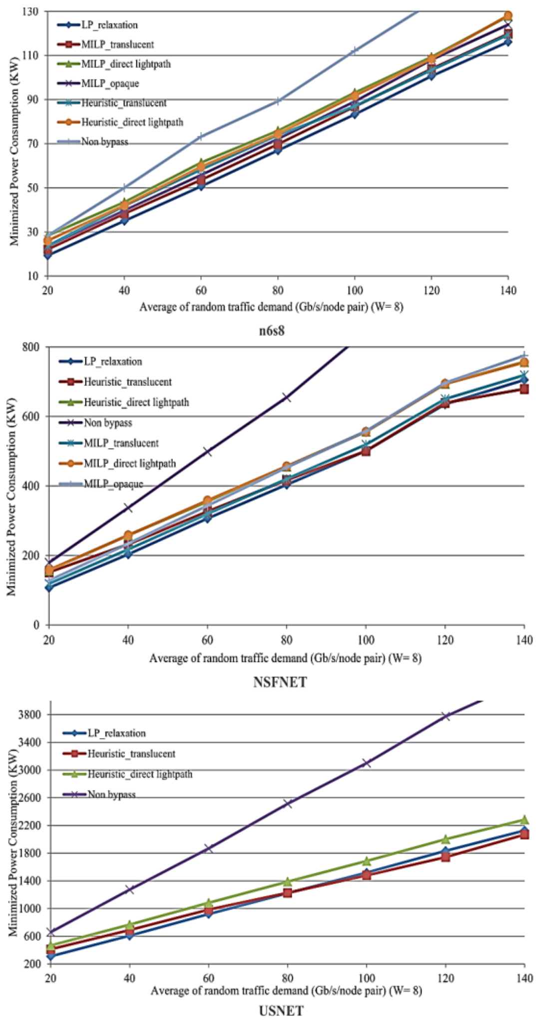


Fig .4 . Comparison of total power consumption of different design strategies

Higher energy consumptions and inferior BW utilization of the direct bypass design scheme refers back to the fact that 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. This is the price we should pay to maintain full transparency over whole network.

The above conclusions can be extended to the larger USNET network since results from heuristic analysis of the multi-hop translucent design provide just an upper estimation to exact optimal values. In addition, the total number of fiber segments which was calculated from heuristics turned to be an upper approximation to the optimal one thereby values of relative BW utilization of the multi-hop translucent design in Fig. 5 (c) should be lower than actual ones.

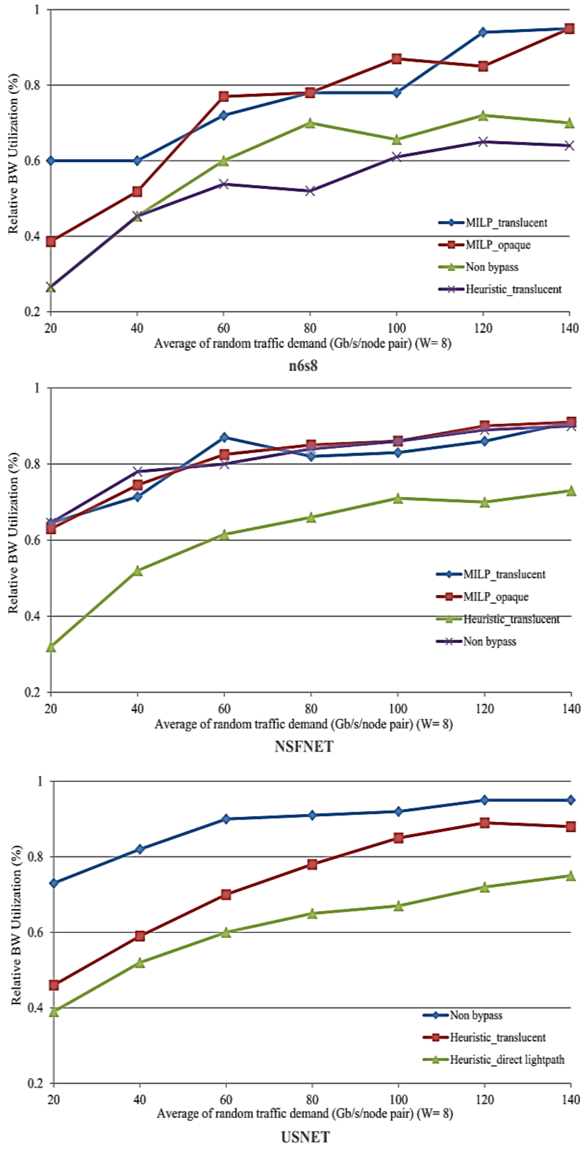


Fig. 5. Comparison of relative BW utilization of different design strategies

As a conclusion, the proposed heuristic for the calculation of power consumption of the multi-hop translucent design obtained satisfactory estimation within 5~7% accuracy and nearly exact results for the case of direct bypass design scheme. Performance of multi-hop translucent design rendered superior than multi-hop opaque design when considering both energy-consumption and BW utility factors.

The variation of total power consumption with the growing scale of wavelength channel capacity per each fiber strand for an average traffic load of 120 erlangs is depicted in Fig. 6. Although none of major energy consuming components are directly affected by expanding transmission capacity, slow decay of power consumption is attributed to noticeable saving in total number of EDFAs which is acquired by scaling down the required fiber strands.

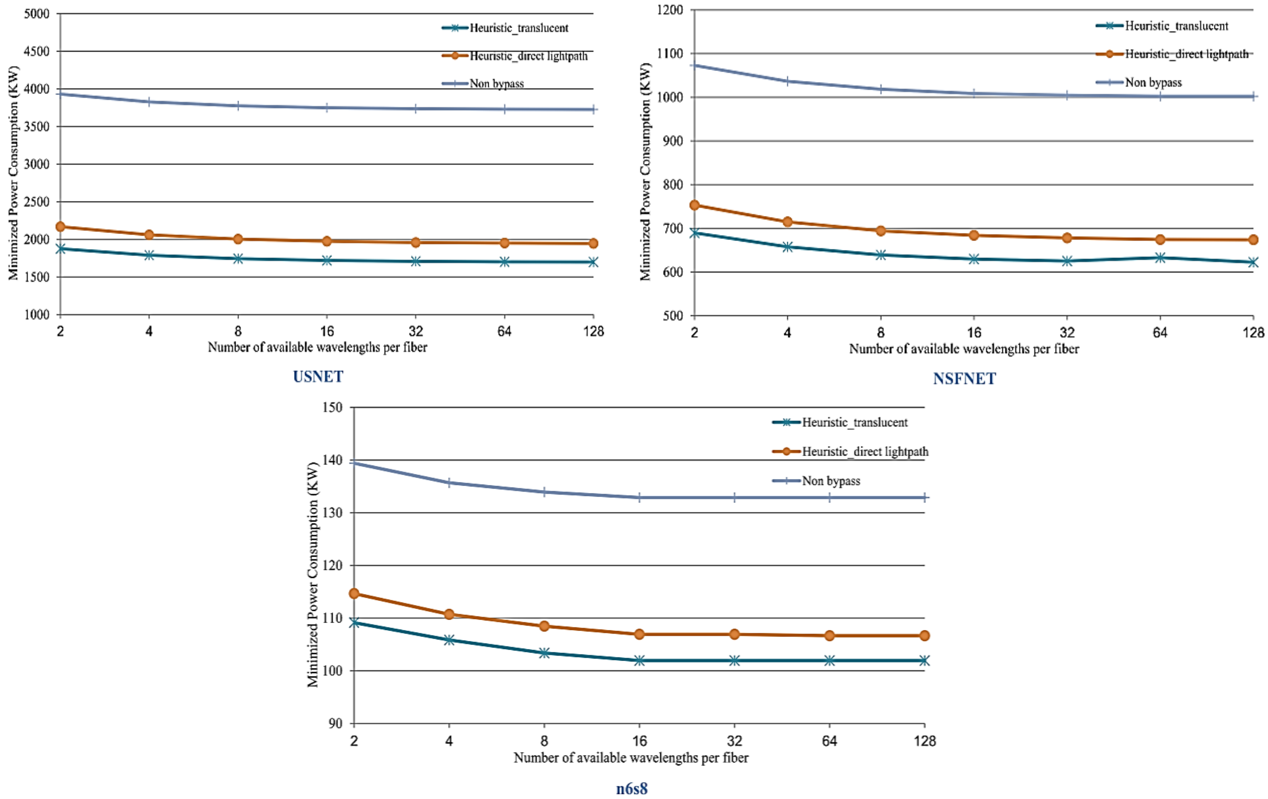


Fig . 6. Variation of total power consumption with wavelength capacity expansion for different design schemes

VI. 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 and proper heuristic algorithms 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 the proposed multi-hop translucent lightpath bypass approach achieved better energy performance than the opaque lightpath bypass design under the same traffic loads. Direct bypass design approach could also achieve good energy performance and acceptable BW utilization at higher traffic loads.

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