Energy Efficient Design for Multi-shelf IP over WDM Networks

Lei Wang, Rui Lu, Qingshan Li, Xiaoping Zheng and Hanyi Zhang

***Abstract*—The explosive growth of Internet drives the development of high performance router. Applying distributed architecture, today's multi-shelf IP core router can provide flexible switch capacity from 1Tbps to 100Tbps. However, the more capacities it has, the more power it consumes, which is becoming a key barrier for bandwidth scaling. This paper studies the energy awareness in design of multi-shelf IP over WDM networks. we analyze the power consumption of different components in multi-shelf IP over WDM networks, including multi-shelf IP core router, ROADM and WDM line system, to deduce the power estimation model. Then, targeting at power minimization, a 2-step MILP design model is proposed, which provides sufficient design details for implementation. Simulation results indicate that, our design approach can minimize the number of both line-cards and router chassis, so performs far better than traditional hop by hop approach in energy saving.**

***Index Terms*—Energy efficient, Line-cards allocation, Multi-shelf IP over WDM network, MILP model, Optical bypass**

I. INTRODUCTION

The rapid growth of network traffic drives the Internet Service Providers (ISPs) to keep their network equipments up-to-date with greater speed and higher switch capacity. However, such growth is accompanied by the increase of power consumption, which is becoming a key barrier to continued bandwidth scaling of Internet [1-7]. Authors of [1] estimate that the power consumption of the Internet occupies approximately 0.4% of the total electricity consumption in broadband-enabled countries, where access rates are on the order of 1 Mb/s. As the Internet expands and access rates increase, this percentage is most likely to rise dramatically (between 1% ~ 10% of the total if access rates increase to 100Mb/s) [7]. Moreover, Energy-wasting network equipments are often placed in a few buildings, which cause a series problem on power supply and cooling [5].

To address this problem, many efforts were devoted on power saving at silicon, chip and system level. Nevertheless, due to the Internet boom, it is far less enough to limit power consumption of high speed equipments if solely rely on system design technique [1,5]. In 2003, authors of [8] pioneered to raise the issues of energy saving in the Internet. After that, Network-level power saving technique attracts more and more attention in both research and industry area. In 2008, authors of [5] created a generic model for router power consumption, and applied Mixed-Integer Linear Programming (MILP) technique to investigate power consumption, performance and robustness in multi-shelf IP network design, configuration and routing. In 2009, authors of [9] firstly taken optical bypass into consideration and proposed an energy oriented model for IP over WDM network. Simulation results indicated that the proposed designs can significantly reduce energy consumption of IP over WDM network. However, it is only a rough model to present power consumption of IP routers by the number of ports being used, which significantly degrade accuracy and energy-saving effect of such designs.

In this paper, we concentrate on the power efficient design problem in high-capacity core networks. Different from single-shelf routing system, multi-shelf one, such as Cisco CRS-1 Carrier routing system [10], uses modular and distributed architecture to integrate multiple points of presence (POP) functions into a single system and provides 1Tbit/s~100Tbit/s switch capacity. In such system, each shelf/chassis consumes a considerable amount of power to support its base modules (alarm/power/fans system, shelf controller and route processor), even if there is not any traffic passing through it. Therefore, it is an interesting question of how to configure each node, assign optical bypass and route the traffic, such that the whole network needs the fewest chassis/shelves and consumes less power on basic modules.

To begin with, we create a power estimation model for multi-shelf IP over WDM networks. Based on Cisco CRS-1 carrier routing system [10-13], we analyze the architecture of multi-shelf IP router and present the power consumption of each component in detail. In optical layer, Reconfigurable Optical Add-Drop Multiplexer (ROADM) is adopted to provide flexible switching and high capacity with low power consumption. So far as we know, this is the first time to take multi-shelf routing system into consideration for energy efficient design in IP over WDM networks. This part is presented in Section II.

Secondly, targeting at minimizing the power consumption of whole network, we formulate the design problem as a MILP program and solve it using AMPL/CPLEX tool. Given the

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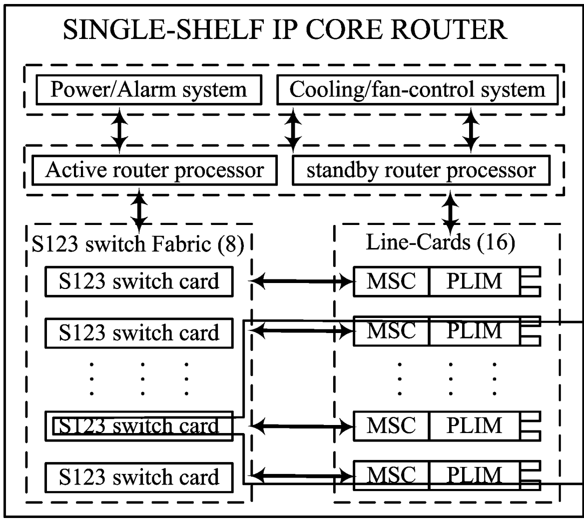


Fig. 1. Architecture of single-shelf routing system.

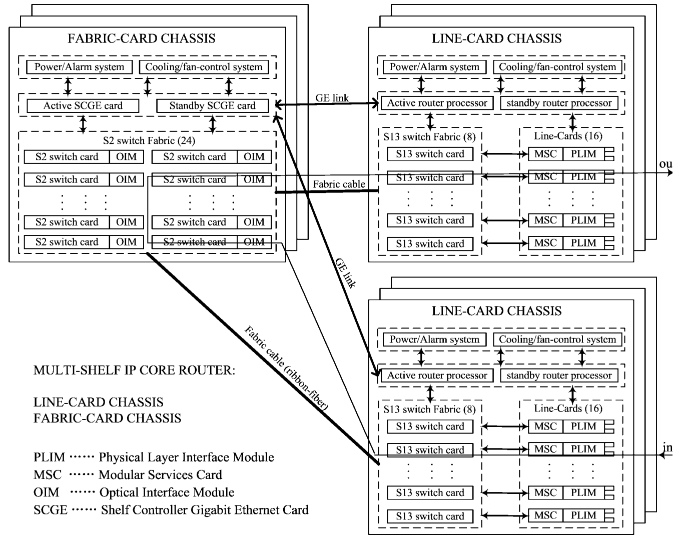


Fig. 2. Architecture of multi-shelf routing system.

network physical topology and traffic matrix, from the results we are able to find power minimized design of 1) how to allocate router line-cards and chassis at each node; 2) how to configure the virtual topology and route each light-path in optical layer; 3) how to aggregate and route IP traffic on virtual topology. The model is based on commercial network equipments, so it provides sufficient details and can be applied in real networks. Furthermore, the transmission limitation of optical bypass is also considered to guarantee Quality of Transmission (QoT). We describe these studies in section III.

Thirdly, to evaluate the energy efficient design, simulations are conducted on several test networks with different traffic load. It is found that, for one thing, the proposed design can minimize the number of router chassis used in the whole network, so to reduce power consumed by basic modules; for another, it applies optical bypass as well, to alleviate power-wasting intermediate packet processing and forwarding in IP layer. Compared to Traditional IP (T-IP) network, the energy efficient design can save power by up to 40% on test networks. This part is presented in section IV.

Finally, section V concludes the whole paper.

II. MULTI-SHELF IP OVER WDM NETWORKS

A. *Single-shelf Routing Systems*

Taking Cisco CRS-1 16-slot single-shelf routing system [12] as an example, it consists 4 main function blocks: line-card, switch fabric, route processor and power/alarm/cooling system, which are all placed in one Line-Card Chassis (LCC), as shown in Fig. 1. More specifically, the line-card is made up of two modules: Physical Layer Interface Module (PLIM) and Modular Services Card (MSC). Each MSC and associated PLIM implement layer 1 through layer 3 functionality. Parts of line-cards are used as aggregation ports for the access of low-end routers, while the others connect to the optical switch node directly by tunable long-reach interfaces. The switch fabric uses a cell-switched, buffered three-stage Benes switch fabric architecture, and receives user data from ingress MSC and performs the switching necessary to route the data to appropriate egress one. The Router Processor (RP) performs the protocol/route processing in the system and distributes forwarding tables to the line-cards. it also provides a control path to each line-card, performs system-monitoring functions and error logging. Moreover, RP needs to communicate with optical control plane to realize IP/optical integration.

Modeled from Cisco single-shelf routing system [5, 12], the power consumption of IP router (E_{IP}) can be expressed as (1):

$$E_{IP} = E_{c0} + \sum_{i=1}^{n_{lc}} \left(E_{l,i} + E_{tp,i}(T_{in,i}, T_{out,i}) \right) \quad (1)$$

Where E_{c0} is the power consumption of a particular LCC with base configuration; n_{lc} refers to the number of line-cards; $E_{l,i}$ represents the power consumption of the *i-th* line-card with idle state (little traffic flows through it); $T_{in,i}$ and $T_{out,i}$ denotes the amount of traffic from input-port and output-port of the *i-th* line-card respectively; $E_{tp,i}(T_{in,i}, T_{out,i})$ is a scaling factor corresponding to the traffic utilization of the *i-th* line card. According to [14], the power consumed in most type of switching architectures has a linear dependence on traffic. So E_{IP} can be expressed as (2):

$$E_{IP} = E_{c0} + \sum_{i=1}^{n_{lc}} \left(E_{l,i} + P_{tp,i} \times (T_{in,i} + T_{out,i}) \right) \quad (2)$$

Where $P_{tp,i}$ denotes the power consumption per traffic unit of the *i-th* line card. However, some experiments extrapolate the power variation due to traffic utilization is about 10% of the total [5], which is less significant compared with those related to line-card configuration. So we ignore the traffic dependent part of power consumption in a core router for simplification, and E_{IP} can be calculated as (3):

$$E_{IP} = E_{c0} + \sum_{i=1}^{n_{lc}} E_{l,i} \quad (3)$$

B. *Multi-shelf Routing Systems*

Cisco CRS-1 multi-shelf routing system [10] is built by interconnecting multiple LCC using one or more Fabric-Card

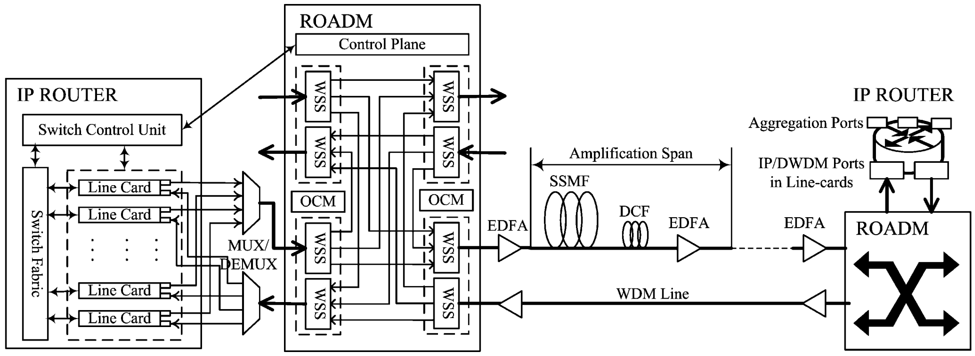


Fig. 3. Architecture of IP over reconfigurable WDM networks.

Chassis (FCC), as shown in Fig. 2. It can scale up to 92Tbit/s, and grows to as many as 72 LCC interconnected by 8 FCC. The LCC is similar as that of single-shelf routing system, except that the switch fabric only performs the functions to implement stage 1 and 3 switching. The FCC contains 3 main function blocks: S2 switch fabric, Shelf Controller Gigabit Ethernet card (SCGE) and power/alarm/cooling system. S2 switch fabric card is made up of two modules: Optical Interface Module (OIM) and S2 switch card. OIM cards host a set of connectors, while S2 switch cards provide the stage 2 function of switch fabric. SCGE card is the local system management for a FCC. It also connects to the control network that links all LCC and FCC.

According to [10], one LCC can support up to 16 line-cards ($CN_{lc} = 16$), while one FCC can support up to 24 S2 switch fabric cards ($CN_{sc} = 24$). In addition, a group of 8 S2 switch fabric cards can support up to 3 LCC. To support n_{lc} line-cards, the number of LCC (n_{lcc}), S2 switch fabric cards (n_{sc}) and FCC (n_{fcc}) are calculated as follows (4):

$$\begin{cases} n_{lcc} = \lceil n_{lc}/CN_{lc} \rceil \\ n_{sc} = 8 \times \lceil n_{lcc}/3 \rceil \quad n_{lc} > 16 \\ n_{fcc} = \lceil n_{sc}/CN_{sc} \rceil \end{cases} \tag{4}$$

The power consumption of multi-shelf IP core router can be calculated as (5), Where $E_{s,i}$ denotes the power consumption of the *i-th* S2 switch fabric card in FCC:

$$E_{M-IP} = \begin{cases} E_{c0} + \sum_{i=1}^{n_{lcc}} E_{l,i} & n_{lc} \le 16 \\ (E_{c0} \times n_{lcc} + \sum_{i=1}^{n_{lcc}} E_{l,i}) + & \\ & n_{lc} > 16 \\ (E_{f0} \times n_{fcc} + \sum_{i=1}^{n_{sc}} E_{s,i}) & \end{cases} \tag{5}$$

C. Architecture of Multi-shelf IP over WDM Networks

The multi-shelf IP over WDM network is made up of two layers: IP layer and optical layer, as shown in Fig. 3. In optical layer, there are two main components: Reconfigurable Optical Add/Drop Multiplexer (ROADM) and transmission line system. The Wavelength Selective Switching (WSS) based ROADM allows any single wavelength or arbitrary group of wavelengths to be dropped or added at any point in the network, which provide a significant improvement on optical flexibility [15-19]. Each bidirectional port of ROADM is composed of a pair of WSS. Optical control plane provides GMPLS based control mechanism. It also interacts with IP core router to get necessary information from IP layer. ROADMs are interconnected with physical fiber links, of which each may contain multiple fibers. Each fiber contains one or multiple amplification span.

The power consumption of ROADM (E_{roadm}) can be expressed as (6):

$$E_{roadm} = E_{r0} + M \times E_d \tag{6}$$

Where E_{r0} is the power consumption of ROADM with base configuration; M denotes the number of DWDM ports; E_d is the power consumption per DWDM port.

The power consumption of WDM line system is mainly contributed by optical amplifiers. It can be expressed as (7):

$$E_{line} = E_a \times (\lceil L/d_a \rceil + 1) \tag{7}$$

Where E_a denotes the power consumption of optical amplifier; L is the total length of optical fiber; d_a is the length of each amplification span.

III. ENERGY EFFICIENT DESIGN MODEL

The power efficient design model needs to consider the following 4 sub-problems: 1) Routing and Wavelength Assignment (RWA) for each light-path demand; 2) Mapping from IP traffic matrix to a set of light-path demands (virtual topology); 3) Aggregation and routing of IP traffic on the virtual topology; 4) cards/chassis configuration for multi-shelf routing system at each node. Considering both optimality and computation complexity, we construct a 2-step MILP model to resolve these problems. The first step is to solve the sub-problem 2, 3 and 4 in IP layer, while the second step is to solve the sub-problem 1 in optical layer. Due to such separation, it cannot be guaranteed to achieve the best results. But realistically, compared to IP routers, optical components consume much less power [9], so the separation has little impact on the final results.

A. Model Statements

(1) Indices

m and n : index of nodes in the physical topology G_p (optical layer). A physical link connects two such end nodes.

i and j : index of nodes in the virtual topology (IP layer).

s and d : index of source and destination nodes of an end-to-end IP traffic demand.

(2) Sets

N : Set of nodes in the network topology G_p . $|N|$ denotes the number of nodes in G_p .

L : Set of physical links in G_p (Physical layer), $(m,n)\in L$.

N_i : Set of transparent reachable nodes from node i . It means that, for each node $j\in N_i$, a transparent light-path can be established between node pairs (i,j) with acceptable QoT (Quality of Transmission). $N_i \subseteq N$.

W : Set of wavelengths in the fiber. $|W|$ denotes the number of wavelength on each fiber link.

$P_{i,j}$: Set of pre-calculated paths from node i to node j , $j\in N_i$. For each path $p\in P_{i,j}$, QoT requirements must be met.

(3) Parameters

B : Capacity (Gb/s) that each line-card/wavelength can carry.

$T_{s,d}$: Amount of traffic (Gb/s) between node pair (s,d) .

ϕ_i : Number of line-cards used as aggregation ports at node i .

$\phi_s = \left\lceil \max(\sum_{d\in N, d\neq s} T_{s,d}, \sum_{d\in N, d\neq s} T_{d,s}) \big/ B \right\rceil$.

$A_{m,n}$: Number of EDFAs in physical link $(m,n)\in L$. $A_{m,n} = \lceil d_{m,n}/d_a \rceil + 1$, where $d_{m,n}$ denotes the length of physical link (m,n), and d_a denotes the length of amplification span.

$\alpha_{m,n}^{i,j,p}$: Binary path-link parameter of path $p\in P_{i,j}$. It takes the value 1 when p traverse link (m,n) .

RN_{wdm} : Maximal number of DWDM ports of one ROADM.

RN_{lcc} : Maximal number of LCC of one multi-shelf core router.

RN_{fcc} : Maximal number of FCC of one multi-shelf core router.

CN_{lc} : Total number of line-cards in one LCC.

CN_{sc} : Total number of S2 switch fabric cards in one FCC.

E_{c0} : Power consumption (kw) of LCC with base configuration.

E_l : Power consumption (kw) per line-card and corresponding switching function.

E_{f0} : Power consumption (kw) of FCC with base configuration.

E_s : Power consumption (kw) per S2 switch fabric card.

E_{r0} : Power consumption (kw) of ROADM with base config..

E_d : Power consumption (kw) per DWDM port in ROADM.

E_a : Power consumption (kw) of EDFA.

(4) Variables

$c_{i,j}$: Integer. Number of wavelength channels between node pair (i,j). Note that, in 2-step model, the first step considers it as variable, but the second step considers it as parameter.

$\lambda_{i,j}^{s,d}$: Amount of traffic of (s,d) that traverse virtual link (i,j).

$h_{i,j}^{p,w}$: Integer. Number of wavelength channels of node pair (i,j) that take path p and wavelength $w\in W$.

$f_{m,n}$: Integer. Number of fibers in physical link (m,n).

θ_m : Integer. Number of add/drop DWDM ports that connect to IP core router in ROADM m .

ρ_m : Integer. Number of transmission DWDM ports that connect to other nodes in ROADM m .

$n_{lc,i}$: Integer. Number of line-cards in node i .

$n_{sc,i}$: Integer. Number of S2 switch fabric cards in node i .

$n_{lcc,i}$: Integer. Number of LCC in node i .

$n_{fcc,i}$: Integer. Number of FCC in node i .

$n_{sg,i}$: Integer. Number of S2 switch group (8) in node i .

δ_i : Binary FCC indicator. It takes the value 1 when $n_{lcc,i} > 1$.

B. 2-Step MILP Design Model

Step 1 (IP layer):

Objective: Minimize

$$\sum_{i\in N}\left((E_{c0}\times n_{lcc,i} + E_l \times n_{lc,i}) + (E_{f0}\times n_{fcc,i} + E_s\times n_{sc,i})\right) \tag{8}$$

Subject to:

$$\sum_{j\in N_i}\lambda_{i,j}^{s,d} - \sum_{j\in N_i}\lambda_{j,i}^{s,d} = \begin{cases} T_{s,d} & i=s \\ -T_{s,d} & i=d \\ 0 & otherwise \end{cases} \tag{9}$$

$\forall i,s,d\in N: s\neq d$

$$\lambda_{i,j}^{i,j} \geq trunc(\lambda_{i,j}/B)\times B \quad \forall i\in N \,\&\, j\in N_i \tag{10}$$

$$\sum_{s,d\in N, s\neq d}\lambda_{i,j}^{s,d} \leq c_{i,j}\times B \quad \forall i\in N \,\&\, j\in N_i \tag{11}$$

$$\begin{cases} n_{lc,i} \geq \sum_{j\in N_i} c_{i,j} + \phi_i & \forall i\in N \\ n_{lc,i} \geq \sum_{j\in N_i} c_{j,i} + \phi_i & \forall i\in N \end{cases} \tag{12}$$

$$n_{lcc,i} \geq n_{lc}/CN_{lc} \quad \forall i\in N \tag{13}$$

$$\delta_i \geq (n_{lcc,i}-1)/1000 \quad \forall i\in N \tag{14}$$

$$\begin{cases} n_{sg,i} \geq \delta_i + (n_{lcc,i}-3)/3 \\ n_{sc,i} = 8\times n_{sg,i} \end{cases} \quad \forall i\in N \tag{15}$$

$$n_{fcc,i} \geq n_{sc,i}/CN_{sc} \quad \forall i\in N \tag{16}$$

$$\begin{cases} n_{lcc,i} \leq RN_{lcc} \\ n_{fcc,i} \leq RN_{fcc} \end{cases} \quad \forall i\in N \tag{17}$$

Step 2 (optical layer):

Objective: Minimize

$$\sum_{i\in N}\left(E_{r0} + E_d\times(\theta_i+\rho_i)\right) + \sum_{(m,n)\in L}\left(E_d\times A_{m,n}\times f_{m,n}\right) \tag{18}$$

Subject to:

$$\sum_{p\in P_{i,j}, w\in W} h_{i,j}^{p,w} = c_{i,j} \quad \forall i\in N \,\&\, j\in N_i \tag{19}$$

$$\begin{cases} \sum_{i,j\in N, i\neq j, p\in P_{i,j}} \alpha_{m,n}^{i,j,p}\times h_{i,j}^{p,w} \leq f_{m,n} \\ \sum_{i,j\in N, i\neq j, p\in P_{i,j}} \alpha_{m,n}^{i,j,p}\times h_{i,j}^{p,w} \leq f_{n,m} \end{cases} \quad \forall (m,n)\in L; w\in W \tag{20}$$

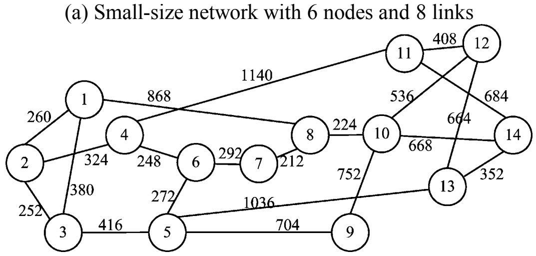
$$\begin{cases} \theta_i \geq \sum_{j\in N, j\neq i, p\in P_{i,j}} h_{i,j}^{p,w} \\ \theta_i \geq \sum_{j\in N, j\neq i, p\in P_{i,j}} h_{j,i}^{p,w} \end{cases} \quad \forall i\in N; w\in W \tag{21}$$

$$\rho_m = \sum_{(m,n)\in L} f_{m,n} \quad \forall m\in N \tag{22}$$

$$\rho_m + \theta_m \leq RN_{wdm} \quad \forall m\in N \tag{23}$$

The objective (8) and (18) is to minimize the power consumption of IP layer and optical layer, respectively.

(a) Small-size network with 6 nodes and 8 links



(b) NSFNET with 14 nodes and 23 links

Fig. 4 Sample networks with fiber length (km) marked on each link

TABLE I. NETWORK PARAMETERS [10, 12, 21, 22]

Parameter	Value	Parameter	Value
E_{c0}	5.8kw	$\|W\|$	40
E_l	0.55kw	B	40Gbps
E_{f0}	4.6kw	RN_{lcc}	72
E_s	0.4kw	RN_{fcc}	8
E_{r0}	0.35kw	CN_{lc}	16
E_d	0.245kw	CN_{sc}	24
E_a	0.06kw	RN_{wdm}	8

Constraint (9) is the flow conservation constraint in IP layer. Constraint (11) ensures that enough light-paths are established between node i and j to accommodate all the IP flows that traverse virtual link (i, j). Constraint (12) guarantees that sufficient line-cards are configured in each core router for traffic aggregation and switch. Constraint (13) ensures that there are enough LCC to support the line-cards at each node. Constraint (14) and (15) guarantee that sufficient S2 switch fabric cards are configured in each core router. Constraint (16) ensures that there are enough FCC to support the S2 switch fabric cards at each node. Constraint (17) says that the maximal number of LCC/FCC is subject to the allowed number of LCC/FCC at each node. Constraint (19) ensures all light-path demands are served in optical layer. Constraint (20) determines the number of fibers on physical link (m,n), and also ensures that any wavelength on a fiber link can not be used more than one time. Constraint (21) and (22) ensures that there are enough add/drop DWDM ports and transmission DWDM ports of ROADM at the node. Constraint (23) ensures that the DWDM ports of each ROADM are subject to the allowed number.

This model remarkably reduces the computation complexity at the cost of lower optimization level. Moreover, it provides sufficient details from line-cards allocation, virtual topology configuration, traffic routing, to ROADM port configuration, fiber deployment, and routing and wavelength assignment of each light-path, which can be applied in real networks.

IV. SIMULATIONS

A. Network Model

In the simulations, two networks are studied: (1) Small-size network with 6 nodes and 8 bidirectional links (6N8L); (2) NSFNET with 14 nodes and 21 bidirectional links (14N21L), as shown in Fig.4. Network parameters are presented in table I.

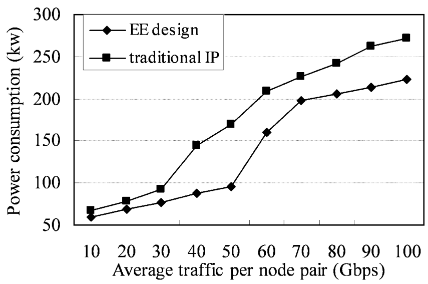
B. Assumptions

1) Each fiber contains 40 wavelengths with digital rate 40 Gbit/s. The length of each amplification span is 80 km.
2) The transmission reach of transparent light-path is limited to 3000 km in optical layer.
3) The K-Shortest Path (KSP) routing algorithm (based on physical distance) is applied to find a set of candidate path in optical layer. The maximal number of path in the set is 5.
4) The average traffic of each node pair is random with a uniform distribution within a center range, $[0.5X, 1.5X]$ (X denotes average traffic per node pair of whole network). The traffic demands are unidirectional.
5) The MILP problems are solved by AMPL/CPLEX 11.0.0 on a desktop with Intel E8500 CPU and 4G memory.

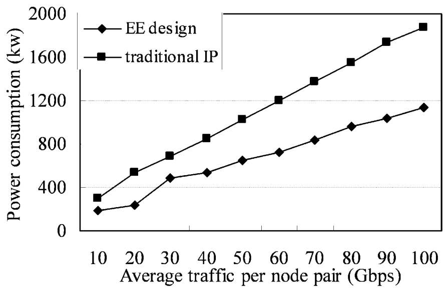
C. Numerical Results and Performance Analysis

Fig. 5(a) shows the results of total power consumption in network 6N8L. Compared with traditional IP approach (hop by hop), Energy Efficient (EE) design can maximally reduce the power consumption from 7.4kw (ATpNP = 10Gbps) to 73.7kw (ATpNP = 50Gbps). By EE design, when ATpNP grows beyond 50Gbps, the switch capacity of single-shelf routing system is not enough, so multi-shelf system is applied with more power consumption to support the added chassis. However, as ATpNP grows from 70Gbps to 100Gbps, EE design can also save energy consumption from 28.7kw (12.7%) to 48.2kw (17.7%). Fig. 6(a) shows the power consumption of different type of components by EE design in network 6N8L. LCC-BC (FCC-BC) denotes the power consumption of line-card chassis (fabric card chassis) with base configuration, while S2-SFC means the power consumption of S2 switch fabric cards. Compared with others, the optical components (ROADM and DWDM line system) consume much less power. When ATpNP is greater than 50Gbps, the use of FCC-BC and S2-SFC lead to more power consumption. However, Line-Cards (LC) and LCC-BC also consume more than 70% power consumption of all. From the results we can deduce that, for power saving, it is best to minimize the number of chassis, and to maximize the number of line-cards per chassis [5].

Fig. 5(b) shows the results of total power consumption in network 14N21L. As ATpNP grows from 10Gbps to 100Gbps, EE design can maximally reduce power consumption from 109.2kw (36.7%) to 739.0kw (39.8%) compared with traditional IP approach. The results in Fig. 6(b) is similar as that of network 6N8L. Fig. 7(a) and Fig. 7(b) show geographic distributions of line-cards with different design approaches in network 6N8L and 14N21L, respectively. It can be observed that by traditional IP approach, the geographic distribution of

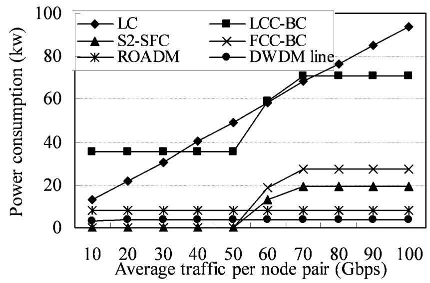


(a) Results in 6N8L

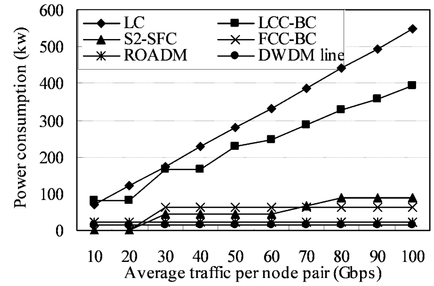


(b) Results in 14N21L

Fig. 5. Total power consumption.

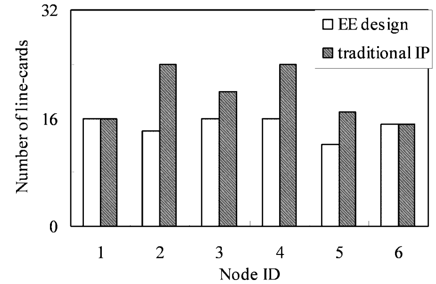


(a) Results in 6N8L

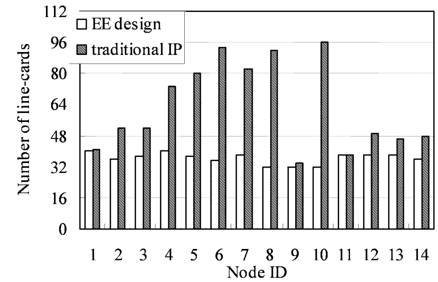


(b) Results in 14N21L

Fig. 6. Power consumption of different components.



(a) Results in 6N8L



(b) Results in 14N21L

Fig. 7. Geographic distributions of line-cards.

line-cards has a large variance. Moreover, the number of line-cards of some nodes just exceeds the capacity threshold, which means one more LCC is needed to carry only a few line-cards. In contrast, EE design shows much more uniform distributions and avoids the "just exceed" condition.

V. Conclusions

As Internet explosively grows, the ever-increasing power demands present a big challenge to continued bandwidth scaling in next generation network. To address this problem, we propose an Energy Efficient design (EE design) approach for multi-shelf IP over WDM networks. For one thing, through power-aware allocation of line-cards and related components of multi-shelf IP core router at each node, EE design can minimize the number of chassis used in the whole network, to reduce the power consumed by base modules. For another, optical bypass is applied by EE design to reduce the number of line-cards used for power wasting packet processing and forwarding in IP layer. Taking both optimality and computation complexity into consideration, we establish a 2-step MILP model for EE design, which provides sufficient details for network configuration and can be used in real circumstance. Simulation results show that, in terms of test networks and traffic matrix, EE design can reduce power consumption by up to 40% compared with traditional IP approach. Nevertheless, 2-step MILP model also presents high computation complexity in large scale network. For further study, we plan to investigate corresponding heuristics based on EE design.

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