A Study of Energy-Aware Traffic Grooming in Optical Networks: Static and Dynamic Cases

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***Abstract*—Less attention has been given to energy aware optical counterparts, compared to the research in energy-aware wireless and ethernet networks. In this paper, we consider energy-aware traffic grooming problems in optical networks for both static and dynamic cases. Rather than simply considering a logical architecture of an optical node, we specifically look further into the modular physical architecture. We show that by reusing already active physical components during request allocations, we can significantly reduce the total number of active components and, hence, total energy consumption in the network, especially when traffic load is low. Since energy usage is an important element of operational expenditure, this approach provides the financial motivation for service providers along with the desired environmental motivation. We present a mathematical formulation of the problems, propose auxiliary graph based heuristics, and justify our cases compared to traditional approaches, based on simulation results.**

***Index Terms*—Energy-efficiency, modular switch architecture, optical networks, traffic grooming.**

I. Introduction

To cope with future rapid growth, resources in backbone networks (e.g., core routers) are often over-provisioned to handle twice the current peak demand [1]–[3]. In most cases, network resources remain active to their full capacities for 24 h a day, 7 days a week, and 365 days a year, regardless of the traffic demand. Studies show that traffic is bursty with idle periods, and has diurnal and weekly variations [4], [5]. Subsequently, network resources remain under-utilized by a wide margin, resulting in huge energy waste. Energy cost is a major part of operating cost (OPEX) of current networks [6], [7]. With the exponential growth of Internet, energy cost in network devices likely to be increased exponentially, unless breakthroughs are achieved in current communication technologies [8]. It has been measured that, in the U.S. alone, the energy spent per year for network infrastructures is on the order of terawatts, thus offering the potential of saving billions of dollar via energy awareness [4], [9], [10]. Note that energy awareness in network components provides savings not only in terms of electricity, but also in terms of other tangible operations and maintenance costs, such as air-conditioning and diesel costs [7].[1] In addition to these economical rewards, there is an important ecological advantage of energy awareness. An estimate by the U.S. Energy Information Administration (EIA) indicates that the generation of one kWh of electricity emits an average of 1.35 lbs of harmful CO_2 [12]. Given the terawatt level energy spending for network infrastructures in the U.S.A., reducing power consumption in networks is expected to reduce CO_2 emission on the order of a million metric tons per year. Because of these economical and environmental rationales, the slogan for greener (i.e., energy-aware) telecommunications is quickly becoming a social, political, and commercial issue. The impact of green optical networks is evident as optical networks have been extended from backbone-only networks to access networks.

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A. Related Studies

A significant body of literature on green wired networks focuses on Ethernet. These studies mainly differ in solutions regarding Ethernet host and NIC cards [13]–[15], link data rate [6], [16], switch functionality [4], [5], and network design [17], [18]. More descriptions are included in [19].

The broad prospect of the IEEE P802.3az Task Force (recently ratified to standard) was to “enable new system level energy management techniques that will save energy beyond the network interface" [6]. As part of the larger goal, our focus in this paper is on intelligent protocols for wired optical networks.

[1]Energy-aware systems dissipate lower heat, and thus benefit from reduced cooling cost. A white paper from Corning Inc., for example, suggests that for each kWh of power required in 10G electronics, at least 2 kWh of power is typically required for cooling [11].

While all-optical networks have high bandwidth capability, the works in [20] and [21] show that optical cross-connects with optical buffering do not provide sufficient power savings when compared with electronically buffered switches. Moreover, the fundamental physics of photons (e.g., zero rest mass, weak photon–photon interaction, and 10^6 times larger size than electrons) manifest greater footprint and power consumption in all-optical networking [22]. A recent study in [23] also highlights the considerable power consumption and dissipation needed by high-capacity network elements, even though we use dynamic circuit switching or a form of hybrid switching that efficiently combines packet, circuit, and burst switching within optical networks. Such a "photonic bottleneck" necessitates energy-efficient protocols for future optical networks.

The survey in [24] provides an overview of energy-conservation approaches across core, metro, and access levels of optical networks. For access networks, energy consumption models are presented in [25], where point-to-point optical links, passive optical networks, fiber to the node, and WiMAX are compared. As an extension, energy consumption in FTTx network variants are studied in [26] with respect to the different access bit rates.

In core networks, a number of works consider the static traffic scenario in which traffic demands are known in advance. A group of works attempts to minimize energy cost by provisioning resources to maximize idle network components, which can then be switched off or placed in a low-power mode [27]–[29]. This problem is proven to be NP-hard, and heuristic solutions are given in [30]–[32]. The authors in [33] design an IP over optical network with the goal of minimizing the total power consumed by routers, transponders, and amplifiers. In [17], the authors suggest that the chassis of a node should accommodate large number of line cards, and line card capacities should closely match required bandwidth. In [34], the authors utilize mixed-line-rate networks. In [35], the authors extend existing IP routing protocols to support energy-efficient routing in IP over WDM networks.

The work in [36] revisits the traffic grooming problem from the energy saving perspective. The authors in [37] model power consumption as a function of the number of lightpaths and total amount of electronically switched traffic. The authors in [38] and [39] route and groom arriving traffic in a manner that attempts to re-use existing lightpaths and activated components in order to minimize the increase in power consumption. The work in this paper is different than other traffic grooming papers in that we employ a modular switch architecture which enables us significant energy saving for both static and dynamic traffic grooming.

B. System Architecture and Objectives

Modern routers are becoming increasingly modular. That is, physical components in routers have functional independency such that they can operate in a distributed manner, e.g., Cisco 12000, Cisco 7600, and Cisco CRS-1 routers [40]. In Cisco CRS-1 routers, modular switch fabrics (along with modular chassis and cards) can be provisioned or disabled (i.e., can be scaled back and forth) when needed [41]. In Cisco Integrated Services Routers, a module-based sleep mode is available

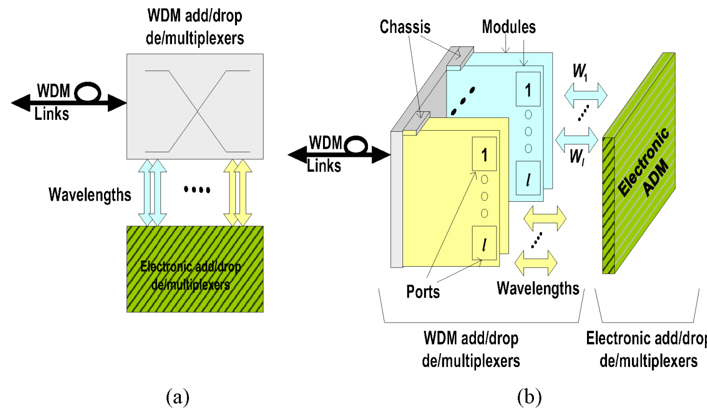

Fig. 1. Optical node with modular physical architecture. (a) Photonic and electronic sections. (b) Modularity in the photonic section.

where power delivery is automatically assigned to network modules, and idle modules neither charge nor dissipate [42]. Such a modular architecture not only mitigates bandwidth scaling and dynamic power management problems, but also provides better fault tolerance [43] and facilitates air-cooling at the points of presence [17].

In this paper, we assume that nodes are modular. A node is divided into two main sections, as shown in Fig. 1(a), photonic and electronic. Typically, the electronic section terminates each incoming wavelength with a transceiver and supports all electronic processing, switching, and routing operations. The electronic section may include systems such as add/drop multiplexers, IP routers, and digital cross-connect switches. For simplicity, we represent the electronic section as an add/drop multiplexer (ADM). The photonic section may include optical cross-connects (passing through and/or switching lightpaths in optical form) or optical ADM (terminating lightpaths and passing the wavelengths to the electronic ADM). We investigate the impact of having a modular architecture in the photonic ADM section of a node in terms of energy consumption. We assume all components in the electronic ADM are always active (powered on). However, the modular photonic ADM allows incoming traffic to be directed to already provisioned ports, modules, and chassis to minimize energy consumption of the node; unused equipment can be powered off. As more traffic enters the node, additional chassis, modules, or ports can be provisioned as needed. System details on the photonic ADM section are shown in Fig. 1(b), where the physical components are grouped into different chassis and modules (or cards). Wavelengths are connected via physical layer interface called ports contained in modules from different chassis. Traffic is routed from one interface to another via a switching fabric contained in one or more module cards. We assume a physical component consumes a fixed electric power when turned on, variable power depending on usage, and low power when idle [4], [44]. Since traffic requests in wavelength division multiplexing (WDM) networks are usually of subwavelength granularity, they are often groomed together in the nodes along their routes [45].

The main contribution of this paper is that we introduce energy awareness in traffic grooming by associating routing to the modular physical node architecture, rather than the logical node architecture traditionally used in optical network research. We show that modular physical nodes offer substantial energy savings in network operation. We consider both static and dynamic cases. In the static case, requests are known *a priori* and can be provisioned based on an optimized order. In the dynamic case, requests arrive one at a time and traffic load in the network varies dynamically following diurnal fluctuation. We propose auxiliary graph (AG) based algorithms to solve the problems. Our primary solution approach is to use currently active components as much as possible during traffic provisioning to increase the number of components in sleep/idle state and to reduce fixed power cost. We provide experimental results comparing our approach to traditional approaches. In this paper, Section II describes problem statements and a mathematical formulation, Section III discusses the construction of AG and heuristic algorithms, Section IV presents simulation results, and Section V concludes this paper.

II. Energy-Aware Traffic Grooming Problems

We assume that the physical topology of a network is already designed and, hence, capital expenditure (CAPEX) is fixed. Our target is to reduce OPEX via minimizing power consumption in the network. As mentioned earlier, we consider modularity in a node at chassis level, module (or shelf card) level, and port (or transmitter–receiver pairs) level. Chipsets of one component can be in idle or sleep mode with slower clock rate, whereas other components remain active. That is, the state of a physical component can be changed dynamically as in [6], [17] and [42]. The given parameters are as follows:

1) the physical topology $G = (V, E)$ of a network, where V is the set of nodes and E is the set of fiber links;
2) node modularity, i.e., the number of chassis per node, the number of modules per chassis, and the number of ports per module;
3) power consumption rates of components (i.e., chassis, modules, and ports) based on states (i.e., active and idle);
4) the number of wavelengths per fiber W and the capacity of each wavelength C.

We also assume that all fiber links are bidirectional and carry the same number of wavelength channels. Transceivers are tunable to any wavelength. A request cannot be split into subgranular connections. In these contexts, we study both static and dynamic energy-aware traffic grooming problems as follows.

A. Static Case

Given a set of subgranular traffic requests (e.g., if C is OC-192, requests can be OC-1, OC-3, OC-12, ..., or OC-192), the following are the objectives.

1) Determine the virtual topology $G_v = (V, E_v)$, where V is the set of nodes in the physical topology and a link $(i, j) \in E_v$ is a unidirectional lightpath from node i to node j.
2) Find routing and wavelength assignment, possibly with grooming, of requests on the virtual topology to minimize the total power consumption in the network.

A good description of general trafficgrooming formulations is available in [45]. Here, we present an integer linear programming (ILP) formulation with respect to our problem.

1) *Notation*:

- s, d: Source and destination of a request.
- m, n: End nodes of a physical fiber-link.
- i, j: End nodes of a virtual-link or lightpath.
- w: Index of wavelengths available.
- y: Speed-granularity of a traffic.
- t: Index of OC-y traffic request(s) for a node pair.
- k: Index of available chassis.
- l: Index of available modules.
- p: Index of available ports.
- M: A very big constant used in weighted function.

2) *Given parameters*:

- N: Number of nodes in the network.
- W: Number of wavelengths per fiber.
- C: Capacity of a wavelength channel.
- P_{mn}: 1 if (m, n) is a physical link; 0 otherwise.
- P_{mn}^w: Wavelength w on fiber P_{mn}, $P_{mn}^w = P_{mn}$.
- N^m: Number of chassis at node m.
- N_k^m: Number of modules at chassis k of node m.
- N_{kl}^m: Number of ports at module l of chassis k of node m; index i is also used for index m.
- $PT_{klp}^{m,n}$: 1 if node pair (m, n) is fiber-linked via port p of module l of chassis k at node m, 0 otherwise.
- EA_{klp}^m: Energy consumption by port p of module l of chassis k at node m when it is active.
- EA_{kl}^m: Energy consumption by module l of chassis k at node m when it is active
- EA_k^m: Energy consumption by chassis k at node m when it is active.
- EI_{klp}^m: Energy consumption by port p of module l of chassis k at node m when it is idle.
- EI_{kl}^m: Energy consumption by module l of chassis k at node m when it is idle.
- EI_k^m: Energy consumption by chassis k at node m when it is idle.
- $\Lambda_{y,sd}$: Number of OC-y connection requests between node s and node d; here, $y \in \{1, 3, 12, ...\}$.

3) *Variables*:

- $P_{mn}^{i,j,w}$: Number of lightpaths of node pair (i, j) routed through fiber link (m, n) on wavelength w.
- V_{ij}: Number of lightpaths from node i to node j in virtual topology; V_{ij} may not be equal to V_{ji}.
- V_{ij}^w: Number of lightpaths from node i to node j on wavelength w; here, $V_{ij}^w > 1$ implies multiple lightpaths taking different paths on wavelength w.
- $\lambda_{ij,y}^{sd,t}$: The tth OC-y request from node s to node d employing node-pair (i, j) as an intermediate virtual link.
- $S_{sd}^{y,t}$: 1 if the tth OC-y request from node s to node d is successfully routed; 0 otherwise.
- PT^i: Total number of ports at node i.
- A_{klp}^m: 1 if port p of module l of chassis k at node m is active (i.e., used by any lightpath), 0 otherwise.

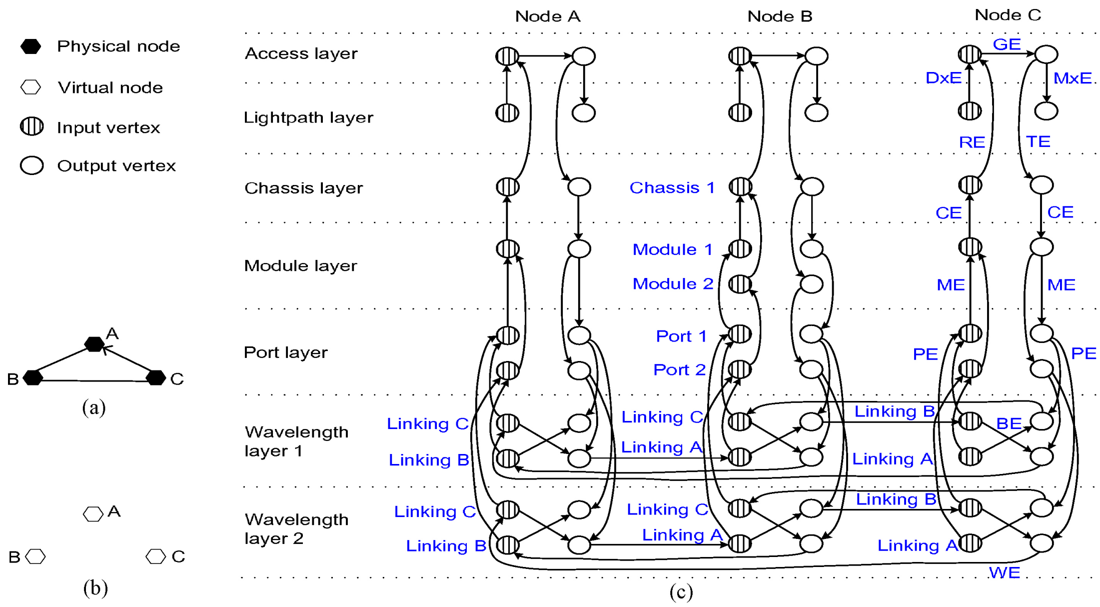

Fig. 2. Example of AG. (a) Given physical topology. (b) Initial virtual topology. (c) Constructed AG.

A_{kl}^m: 1 if module l of chassis k at node m is active (i.e., used by any lightpath), 0 otherwise.

A_k^m: 1 if chassis k at node m is active, 0 otherwise.

4) *Constraints*:

The total number of ports available at node i is the summation of ports in all modules of all chassis, that is

$$PT^i = \sum_k \sum_l N_{kl}^i. \tag{1}$$

To ensure that the number of lightpaths between a node pair (i, j) does not exceed the number of ports

$$\sum_j V_{ij} \leq PT^i \ \forall i \tag{2}$$

$$\sum_i V_{ij} \leq PT^j \ \forall j. \tag{3}$$

The total lightpaths between node-pair (i, j) is composed of all lightpaths on different wavelengths between this pair. Hence

$$V_{ij} = \sum_w V_{ij}^w. \tag{4}$$

To obey flow conservation in a node

$$\sum_m P_{mq}^{i,j,w} = \sum_n P_{qn}^{i,j,w} \ \forall i, j, w, q, \ q \neq i, j \tag{5}$$

$$\sum_m P_{mi}^{i,j,w} = 0 \ \forall i, j, w \tag{6}$$

$$\sum_n P_{jn}^{i,j,w} = 0 \ \forall i, j, w. \tag{7}$$

For a lightpath between node-pair (i, j) on wavelength w, the number of outgoing (or incoming) lightpaths at the origin (or termination) is equal to the total lightpaths, that is

$$\sum_n P_{in}^{i,j,w} = V_{ij}^w \ \forall i, j, w \tag{8}$$

$$\sum_m P_{mj}^{i,j,w} = V_{ij}^w \ \forall i, j, w. \tag{9}$$

To prevent a wavelength w of a fiber (m, n) being used by multiple virtual links,

$$\sum_{i,j} P_{mn}^{i,j,w} = P_{mn}^w \ \forall w. \tag{10}$$

On the virtual topology, flow conservation also holds true

$$\sum_i \lambda_{id,y}^{sd,t} = S_{sd}^{y,t} \ \forall s, d, y, \ t\epsilon[1, \Lambda_{y,sd}] \tag{11}$$

$$\sum_j \lambda_{sj,y}^{sd,t} = S_{sd}^{y,t} \ \forall s, d, y, \ t\epsilon[1, \Lambda_{y,sd}] \tag{12}$$

$$\sum_i \lambda_{is,y}^{sd,t} = 0 \ \forall s, d, y, \ t\epsilon[1, \Lambda_{y,sd}] \tag{13}$$

$$\sum_j \lambda_{dj,y}^{sd,t} = 0 \ \forall s, d, y, \ t\epsilon[1, \Lambda_{y,sd}]. \tag{14}$$

For the flow conservation of intermediate nodes

$$\sum_i \lambda_{iq,y}^{sd,t} = \sum_j \lambda_{qj,y}^{sd,t} \ \ \forall s, d, q, \ \ q \neq i, j, \ \ t\epsilon[1, \Lambda_{y,sd}]. \tag{15}$$

To ascertain that aggregated traffic meets channel capacity

$$\sum_{y,t} \sum_{s,d} y \cdot \lambda_{ij,y}^{sd,t} \leq C.V_{ij} \ \forall i, j. \tag{16}$$

To compute power consumption of ports being used

$$A_{klp}^m \leq PT_{klp}^{m,n} \cdot \sum_{i,j,w} P_{m,n}^{i,j,w} \ \forall k, l, p \tag{17}$$

$$A_{klp}^m \geq PT_{klp}^{m,n} \cdot P_{m,n}^{i,j,w} \ \forall k, l, p, i, j, w. \tag{18}$$

Active modules are those that contain used ports

$$A_{kl}^{m} \leq \sum_{p} A_{klp}^{m} \ \forall k, l \tag{19}$$

$$A_{kl}^{m} \geq A_{klp}^{m} \ \forall k.l. \tag{20}$$

For determining active chassis

$$A_{k}^{m} \leq \sum_{l} A_{kl}^{m} \ \forall k \tag{21}$$

$$A_{k}^{m} \geq A_{kl}^{m} \ \forall kl. \tag{22}$$

The total energy consumption takes into account chassis, modules, and ports, in active or idle state, that is

$$\begin{aligned} \text{Energy} = \sum_{m} \sum_{k} (A_{k}^{m} \cdot EA_{k}^{m} + (1 - A_{k}^{m}) \cdot EI_{k}^{m} \\ + \sum_{l} (A_{kl}^{m} \cdot EA_{kl}^{m} + (1 - A_{kl}^{m}) \cdot EI_{kl}^{m} \\ + \sum_{p} (A_{klp}^{m} \cdot EA_{klp}^{m} + (1 - A_{klp}^{m}) \cdot EI_{klp}^{m}))). \end{aligned} \tag{23}$$

5) *Objective*:
We have to maximize the total successfully-routed requests. We also want to minimize the total energy consumption. Hence, we optimize a weighted summation

$$\min \left(\sum_{y,s,d,t} y \cdot (1 - S_{sd}^{y,t}) \cdot M + \text{Energy} \right)$$

where $P_{mn}^{i,j,w}$, $S_{sd}^{y,t}$, A_{k}^{m}, A_{kl}^{m}, $A_{klp}^{m} \in \{0, 1\}$, V_{ij}, V_{ij}^{w}, $PT^{i} \in Z^{+}$, and (1) to (23).

B. Dynamic Case

In this case, we assume that requests arrive dynamically and are uniformly distributed among nodes. Since the traffic load in backbone networks follows a predictable daily cycle and has peaks and valleys as the sun moves [46], [47], we model such a time of the day dynamism in this paper. We do not consider the "time-zone dynamism" as in [46] and [47].

Our objective is to provision incoming dynamic requests with a routing and wavelength assignment, possibly grooming with existing lightpaths, that minimizes the total power consumption in the network.

III. Energy-Aware Grooming Algorithms

Since the traffic grooming problem is NP-hard [45], we approach both static and dynamic cases with heuristic algorithms. We propose heuristics using an AG model. We first build an AG representing the architecture of a given network, assign costs proportional to the energy consumption rate of components, and then apply shortest path algorithms on the AG.

A. Auxiliary Graph Model

The purpose of the AG is to model relationships among physical components, wavelengths, and lightpaths of a WDM network. That is, both physical and logical topologies are combined with appropriate costs assigned to links in the AG. Such an approach simultaneously considers multiple subproblems included in the traffic grooming problem (e.g., virtual topology selection, routing on virtual topology, wavelength assignment, etc.) and can achieve superior performance compared to an approach where these subproblems are considered one at a time [48]–[50].

We describe the AG with an illustrative example shown in Fig. 2. A 3-node physical topology is given in Fig. 2(a). The associated logical topology is drawn in Fig. 2(b), where there is no link since no lightpath has yet been established. The corresponding AG is constructed in Fig. 2(c) that has W+5 layers for each physical node, where W is the number of wavelengths on a fiber. Like Fig. 2(b), no lightpath has yet been set up in Fig. 2(c). Each layer has two group of vertices: inputs and outputs. The layers and connectivity among vertices are described below.

1) *Access layer*: The very first layer has exactly two vertices: an input vertex and an output vertex. A traffic flow begins from the output vertex and ends at the input vertex. An edge from the input to the output vertex is called a grooming edge as marked in Fig. 2(c).
2) *Lightpath layer*: Next to the access layer is the lightpath layer containing input and output vertices. An optical path originates at the output vertex and terminates at the input vertex in this layer. An edge from the output vertex of the access layer to the output vertex of the lightpath layer is a multiplexing edge. An edge from the input vertex of the lightpath layer to the input vertex of the access layer is a demultiplexing edge.
3) *Chassis layer*: This layer contains a pair of input-output vertices for each chassis in a node. Therefore, the number of vertices in this layer is two times the number of chassis in the node. In the example of Fig. 2, each node has one chassis. An edge from the output vertex of the access layer to the output vertex of the chassis layer is a transmitter edge. An edge from the input vertex of the chassis layer to the input vertex of the access layer is a receiver edge.
4) *Module layer*: The number vertices in the module layer is two times the total number of modules (i.e., cards in chassis slots) in a node. In Fig. 2(c), node A has one module, node B has two modules, and node C has one module. An edge between the chassis and module layers is called a chassis edge (CE).
5) *Port layer*: The number vertices in the port layer is two times the total number of ports in a node. In the example of Fig. 2(c), each node has two ports. The ports of node B correspond to two different modules. An edge between the module and port layers is called a module edge (ME).
6) *Wavelength layers*: For each wavelength, there is a dedicated layer. For example, in Fig. 2(c), W = 2 and thus two such layers exist. The number vertices in a wavelength layer is two times the node-degree (i.e., the number of neighboring nodes). For a physical link from node A to node B, there is an edge from the output vertex of a wavelength layer of node A to the input vertex of the same wavelength layer of node B (and it is replicated for each wavelength layer, assuming that

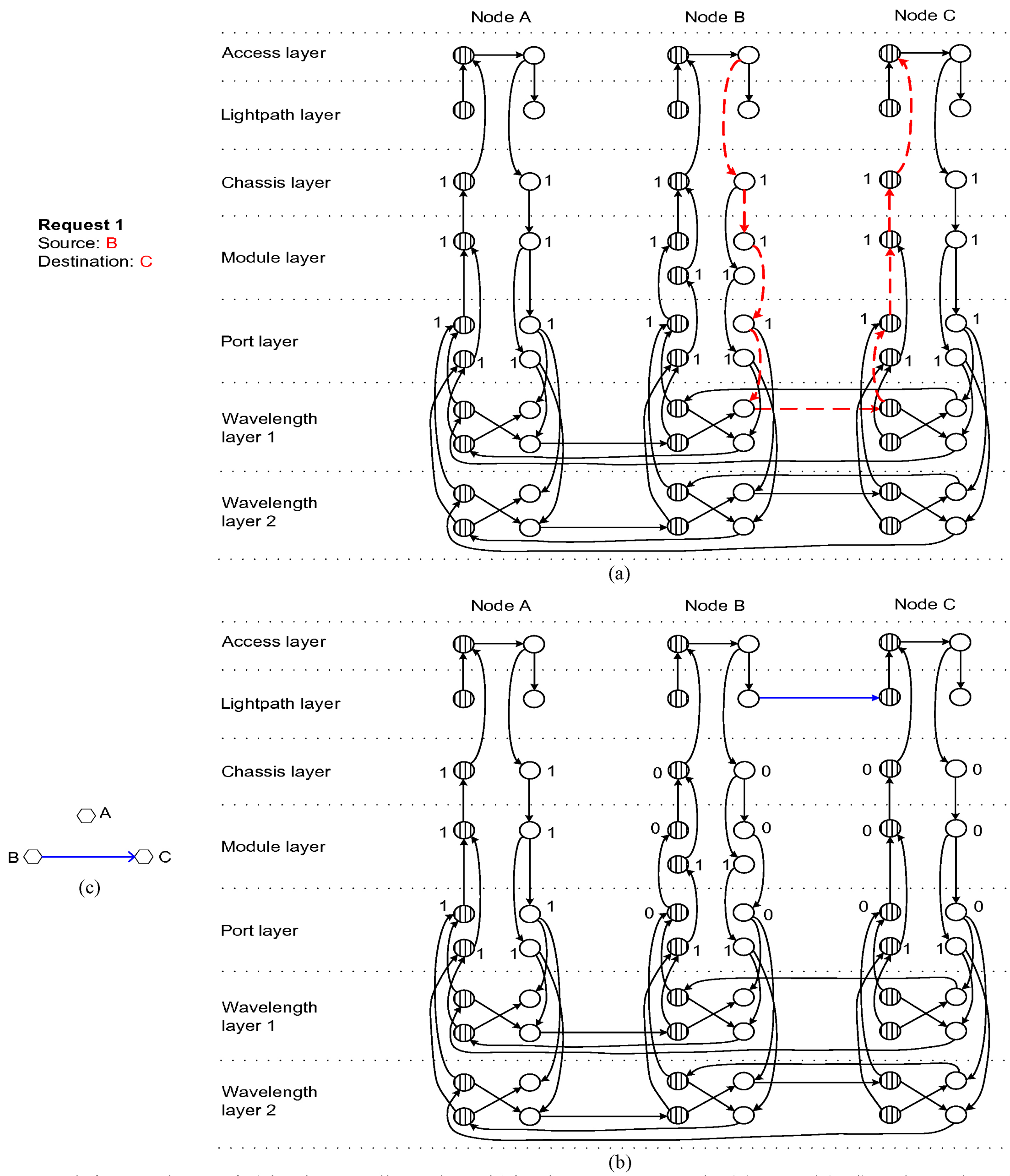

Fig. 3. Finding a path from node B to C. "1" indicates idle mode and "0" indicates active mode. (a) Dotted (red) path is selected as a shortest path. (b) Lightpath is created from node B to C and corresponding wavelength-link is removed. (c) Updated virtual topology.

each fiber has the same number of wavelengths). Such edges are called a wavelength-link edges (WE). An edge between the port and wavelength layers is called port edge (PE). An edge from the input vertex to the output vertex of the same wavelength layer is a bypass edge (BE), which corresponds to the optical bypass in a node. Since we assume that there is no optical wavelength converter, two different wavelength layers have no direct connections.

To understand how the AG is used in request allocations, instances are given in Figs. 3 and 4. Inactive/idle components are marked "1" and active components are marked "0." Costs of edges (i.e., CE, ME, and PE) are set high for those associated with inactive components and are set low for those associated with active components. If a request from a source to a destination traverses the wavelength layer in the AG, corresponding WEs are removed and a lightpath-link edge is established in the lightpath layer between two nodes. For example, a request from node B to node C in Fig. 3(a) is routed along the shortest path as shown in dotted line. The lightpath is then established at the lightpath layer and the wavelength-link used is removed as depicted in Fig. 3(b). The updated virtual topology is shown in Fig. 3(c). As another request from node B to node A arrives in Fig. 4(a), a path is found bypassing at node C (dotted line) that minimizes traversing inactive components. If energy awareness is not a concern, a direct path from node B to A may be chosen where more components need to be activated. This direct path and the previous path both require the

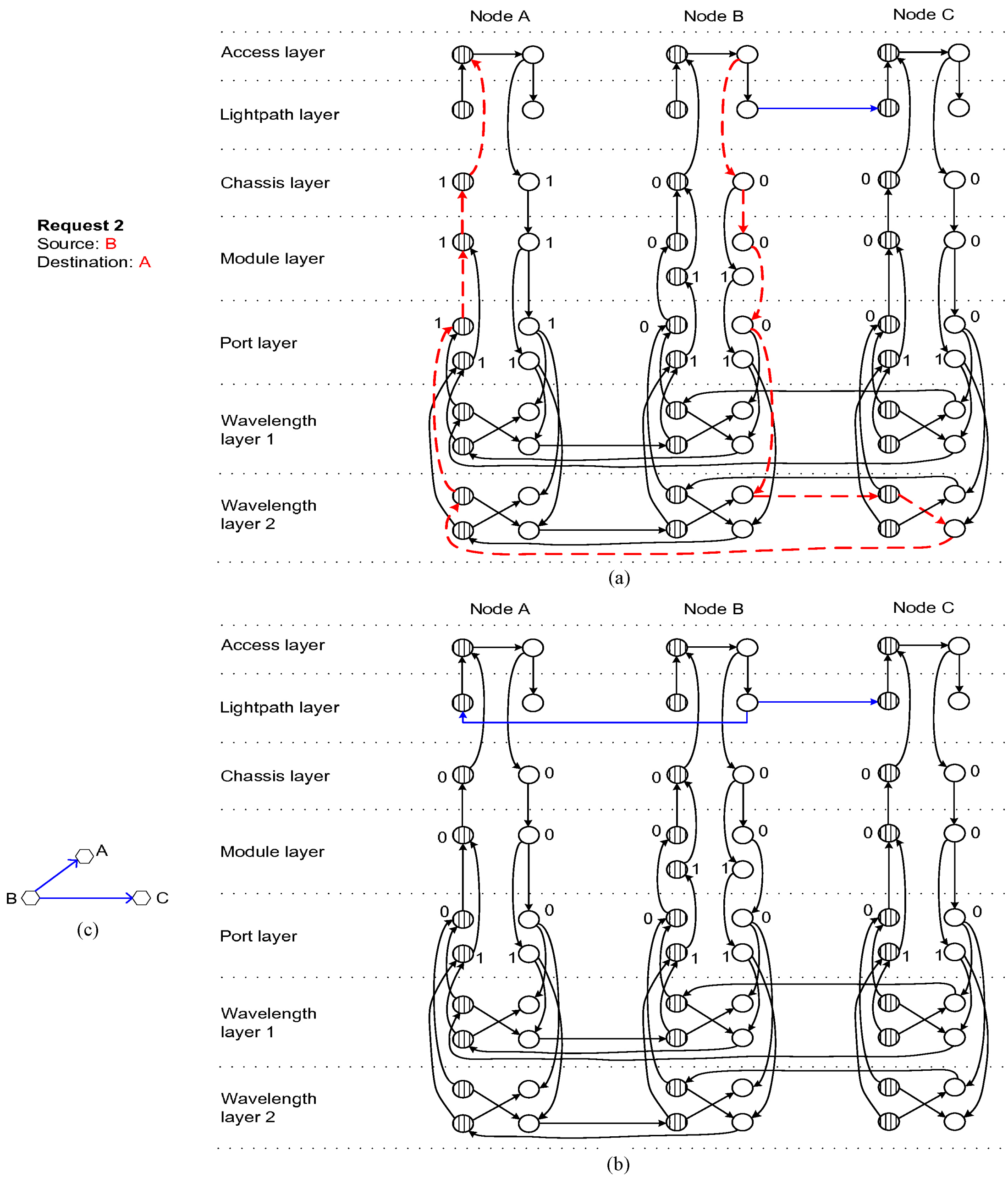

Fig. 4. Finding a path from node B to A. (a) Dotted (red) path is selected as a shortest (energy saving) path. (b) Lightpath is created from node B to A and corresponding wavelength-links are removed. (c) Updated virtual topology.

same number of transceivers, but the previous path activates fewer components, thus saving power. The newly established lightpath and updated wavelength-links are reflected in the AG in Fig. 4(b) and in the virtual topology in Fig. 4(c).

The total number of vertices in the AG for one node is $2\times$ [2 + (number of chassis, modules, and ports) + ($W\times$ node-degree)]. This number is a constant and, therefore, the AG model remains tractable.

B. Request Allocation

Static case: For the static case, we apply two heuristics over the proposed AG model: request size based (RSB) and link utilization based (LUB) traffic allocation. In RSB, source-destination pairs are sorted by total demand from a source to a destination and served in that order. In LUB, source-destination pairs are served in the sorted order of link utilization. Link utilization for a pair is calculated by the total demand divided by the shortest physical distance (hop count) between the pair. Both heuristics have a polynomial-time complexity. The algorithm is outlined in Fig. 5. For each request r from the sorted node-pairs L, we first delete lightpath-links from the AG that have lower available capacities than the demand of r. Then, we find the shortest path on the AG that may use existing lightpath-links to groom requests and/or establish new lightpath-links. We continue the steps until all requests are considered in order.

Dynamic case: For the dynamic case, we follow lines 4–10 of Fig. 5. That is, for a request arrival, the least cost path on the

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Input: A physical topology, a set of requests
Output: A virtual topology with traffic grooming
Pseudo-code:
1.  L ← Node pairs in sorted order of total demand
        (for RSB) or link utilization (for LUB)
2.  Choose the first node pair (s, d) from L
3.  For each request r from s to d
4.      If (capacity of a lightpath < demand of r)
5.          Delete the lightpath from AG
6.      Find the shortest path p from the output
            vertex of the access layer of s to the input
            vertex of the access layer of d
7.      If (p does not exist)
8.          Block request r
9.      Else
            Allocate r along p
10.     Add the lightpaths deleted in line 5
11. L ← L − {(s, d)}
12. If (L ≠ empty)
13.     Go to line 2
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Fig. 5. Pseudocode of the algorithm.

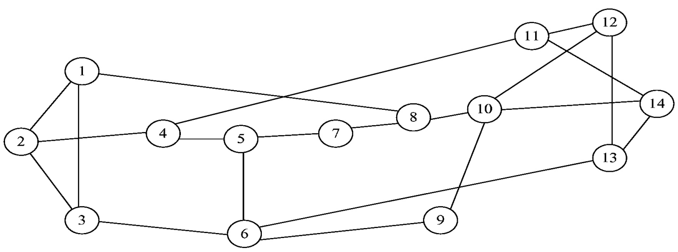

Fig. 6. Network topology with 14 nodes and 21 links.

TABLE I
WEIGHT ASSIGNMENTS OF EDGES IN THE AUXILIARY GRAPH

Edge type	Energy-aware schemes	Other schemes
Grooming edge	20	20
Mux/demux edge	0	0
Transceiver edge	200	200
Lightpath edge	1	1
Chassis edge (idle)	400	0
Chassis edge (active)	0	0
Module edge (idle)	300	0
Module edge (active)	0	0
Port edge (idle)	100	0
Port edge (active)	0	0
Bypass edge	0	0
Wavelength-link edge	10	10

AG is chosen dynamically. The path may traverse an existing lightpath-link which implies grooming. If the path traverses the wavelength layer, the corresponding wavelength-link edges are removed to establish a new lightpath-link edge in the lightpath layer. For a request departure, the wavelength-link edges used in the lightpath are deallocated, if no other requests are using that lightpath.

IV. Experimental Results

We examine the performance of traffic grooming, with and without energy awareness, in terms of energy conservation, request blocking, lightpath length, and resource utilization. We assign the weight of links in the AG based on optimization objectives. For example, when energy awareness is not a concern, we use high weight (or cost) for transmitter and receiver edges as in the "MinLP" policy in [48]. That is, with such a cost assignment, algorithms using the shortest path on the AG will find paths for a request where the number of lightpaths set up is reduced. We call this scheme "traditional" grooming. When energy awareness is a concern, we assign cost proportional to the energy consumption of different components of a switch. For example, in the Cisco Catalyst 6500 series, the approximate power usage for a port is 3 W, a line card/module is 315 W, and a chassis is 375 W (including power consumption for switching fabric, fan, and other parts) [4], [44]. We use these power consumption rates in our case studies and proportionally set the weights of chassis edges, module edges, and port edges. Table I lists the weight assignments of different edges in the AG.

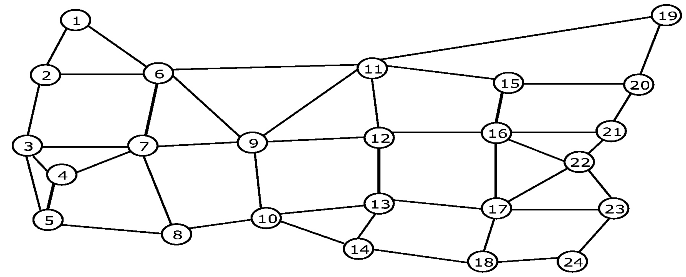

Fig. 7. Network topology with 24 nodes and 43 links.

We experiment on two well-known NSF networks: 14-node (Fig. 6) and 24-node (Fig. 7) networks. The 14-node network has 21 bidirectional links. Each node is assigned at most two chassis, two modules per chassis, and two ports per module. The 24-node network has 43 bidirectional links. Each node is assigned at most three chassis, four modules per chassis, and four ports per module. We assume that wavelength capacity is OC-192 and traffic requests are of subwavelength granularity (i.e., OC-1, OC-3, OC-12, OC-48, or OC-192). The default value for W is 4.

In the dynamic case, we simulate time of the day dynamism. We imitate a traffic profile taken from a 10 GbE Atlanta-Houston connection on a working day in the Internet2 backbone network [51]. We scale the traffic profile based on the network under consideration such that the network capacity remains more than twice the peak hour demand [1]–[3]. The network capacity is measured by ($2\times$ number of links $\times$ number of wavelengths per link $\times$ wavelength capacity) and the load added to the network by a traffic request is measured by (request size $\times$ shortest hop distance between the source and the destination).

As discussed in the previous section, for both energy-aware and traditional traffic grooming, we implement two heuristics, namely RSB and LUB, in the static case, and a simpler heuristic taking one request at a time in the dynamic case. In the results that follow, each data point is averaged from 100 experiments and presented with a 95% confidence interval.

A. Comparisons on Energy Usage for the Static Case

We first observe energy usage for a network under different loads (i.e., total requests). The total load in the

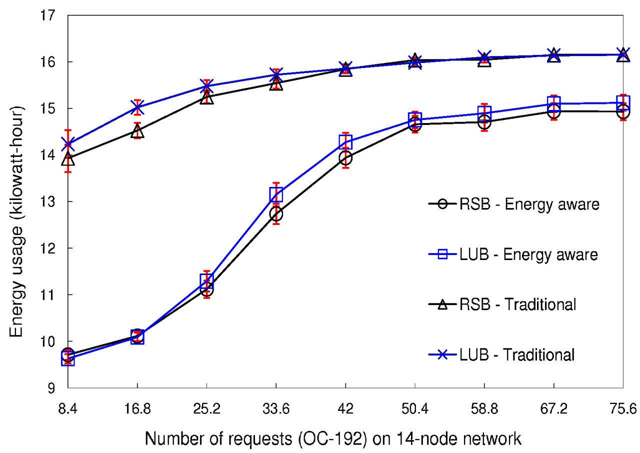

Fig. 8. Energy consumption in the 14-node network.

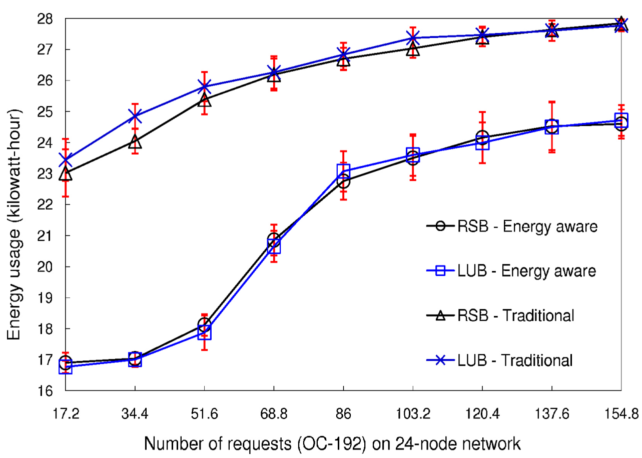

Fig. 9. Energy consumption in the 24-node network.

14-node network varies from 8.4 OC-192 units (approximately 10% load to the network capacity) to 75.6 OC-192 units (approximately 90% load to the network capacity). At each point, we enumerate the number of components required to be active. We then compute total energy consumption at rates of 375 W/chassis, 315 W/module, and 3 W/port [4], [44]. As Fig. 8 depicts, total energy consumed in kilowatt-hour unit for energy-aware grooming is always lower than that for traditional grooming. We find that significantly lower energy consumption can be obtained when the traffic load is low. Energy consumption increases quickly as traffic load increases and more network components become activated, but it is still much lower than traditional schemes. We also find that RSB-energy aware and LUB-energy aware (likewise, RSB-traditional and LUB-traditional) are similar in their behaviors, with RSB approaches showing slightly better energy saving than LUB approaches. The reason is that requset-size based sorting in RSB leads better grooming (i.e., filling up wavelength-capacity more uniformly).

For the 24-node network, the total load aries from 17.2 OC-192 units (approximately 10% load to the network capacity) to 154.8 OC-192 units (approximately 90% load to the network capacity). As Fig. 9 shows, the four schemes exhibit similar performance as in the 14-node network, except

TABLE II
ANNUAL ENERGY CONSUMPTION AND FINANCIAL IMPLICATIONS

Nodes	Schemes	Energy usage (kWh)	Cost (1000 U.S. $)	Saving (1000 U.S. $)	% of saving
14	100% active	142096	16	–	–
14	RSB-traditional	133578	15	1	6
14	RSB-energy aware	97406	11	5	31
24	100% active	380718	42	–	–
24	RSB-traditional	222423	24	17	40
24	RSB-energy aware	158760	17	24	57

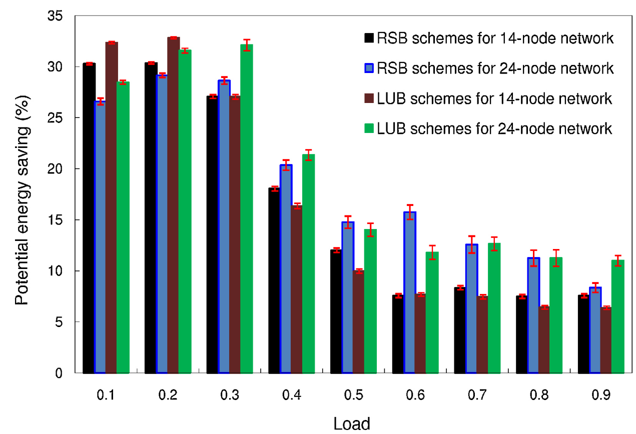

Fig. 10. Percentage of energy saving for different cases.

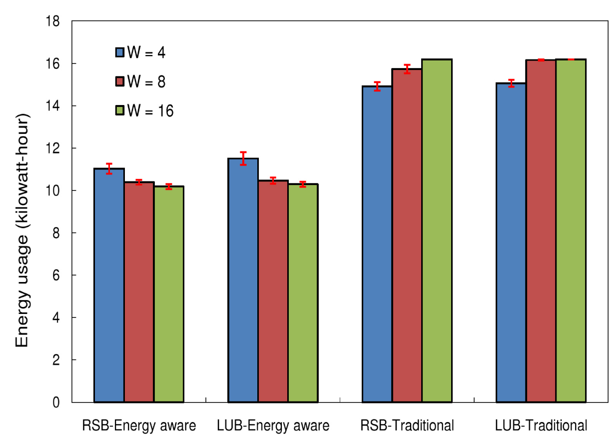

Fig. 11. Energy usage for different wavelengths in 14 nodes.

that total energy consumed is higher in the bigger network since more physical components are involved in the latter case.

For both networks, the percentage of energy saving at low load can be as much as 30% (Fig. 10). At high load, the saving is about 8% for 14 nodes and 12% for 24 nodes. That is, the bigger the network is, the more energy saving potential for carefully routed requests. These results, however, do not include energy expense for components that are not being used by any requests. In practice, all devices, even if not being used, are usually kept active in current telecommunication networks. To see this effect, we calculate the total energy consumed by all devices in the network (we refer to it as "100% active") and compare the results with our schemes for

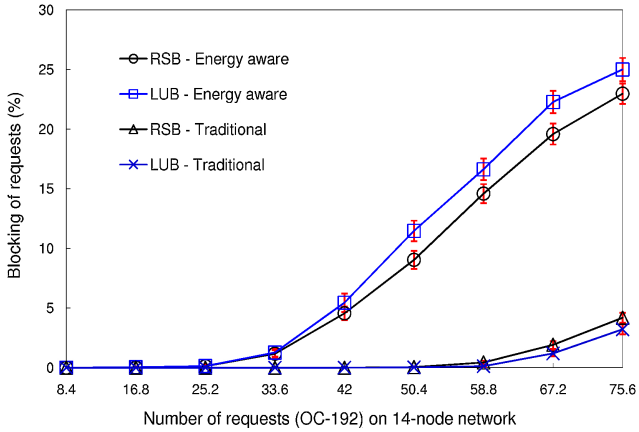

Fig. 12. Blocking of requests in the 14-node network.

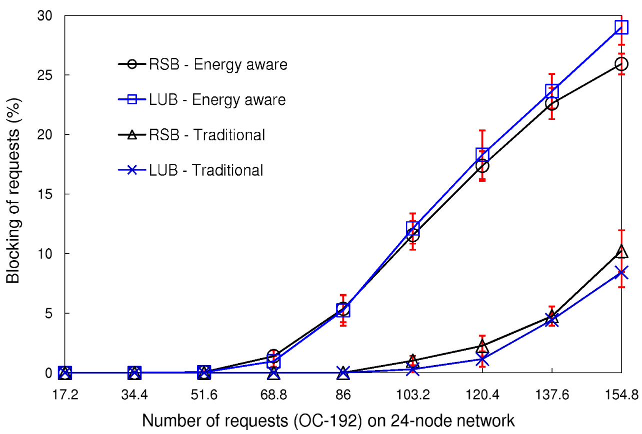

Fig. 13. Blocking of requests in the 24-node network.

30% load. As Table II shows, the annual power consumption is much higher for 100% active 14-node and 24-node networks. Accordingly, at a rate of 11 cents/kWh, our approaches suggest monetary saving on the order of thousands of U.S$ per year. For example, the annual OPEX saving in RSB-energy aware can be $5K for 14 nodes, which is 31% of OPEX in 100% active networks. The saving is even higher, $24K or 57%, for 24 nodes. Similar achievements are also found in LUB-energy aware. Note that, in the energy calculation, cooling cost for heat dissipation (e.g., air conditioning) is not taken account. However, the cascading effects of lower energy consumption can still be perceived: lower energy consumption dissipates lower heat, which reduces cooling cost at the point of presence and decreases OPEX further.

We vary wavelengths, W per link from 4 to 16 and observe that the more wavelengths are available, the better possibility of re-using already active components during energy-aware traffic grooming. Consequently, our schemes have lower energy usage at higher values of W as depicted in Fig. 11 for 14-node networks at load of 30%. In traditional cases, the reverse trend is observed since higher W allows more shortest paths on different components for a given node-pair, whether or not the components are in use (i.e., component re-use is minimized).

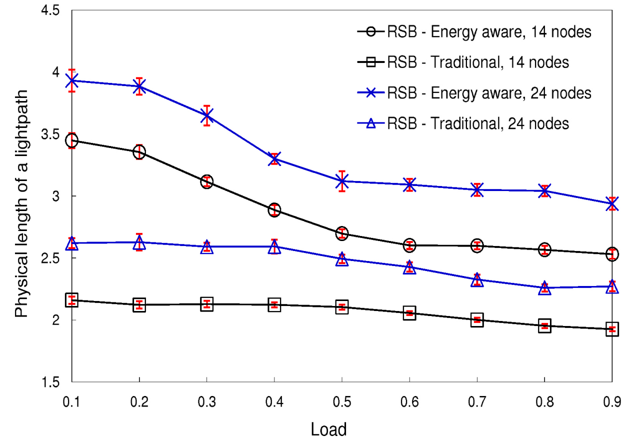

Fig. 14. Average length (hop count) of a lightpath.

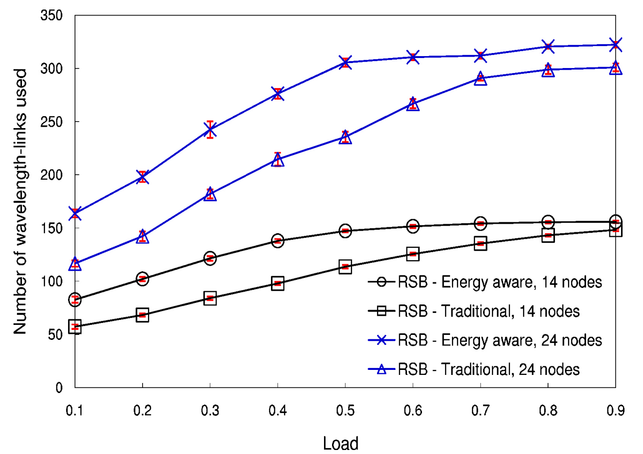

Fig. 15. Usage of wavelength-links per request.

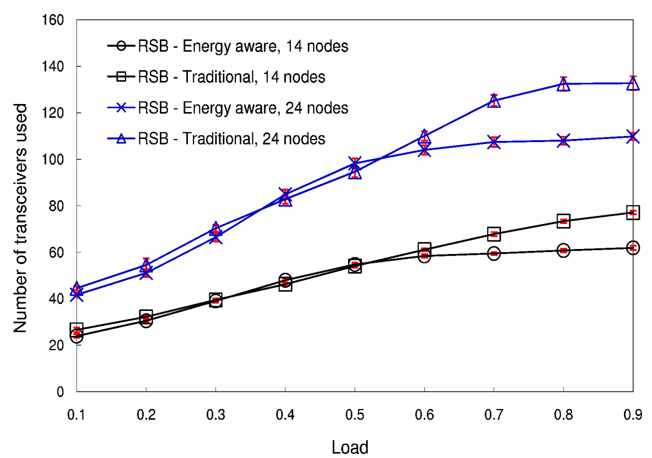

Fig. 16. Use of transceivers.

B. Comparisons on Other Properties for the Static Case

We study blocking probability under varying loads. As expected, Fig. 12 (for 14 nodes) and Fig. 13 (for 24 nodes) show that blocking of requests is higher at higher load. In both networks, RSB-energy aware performs better compared to LUB-energy aware, but RSB-traditional performs poorly compared to LUB-traditional. The LUB mode prioritizes requests with better link utilization. The weight assignments in the AG

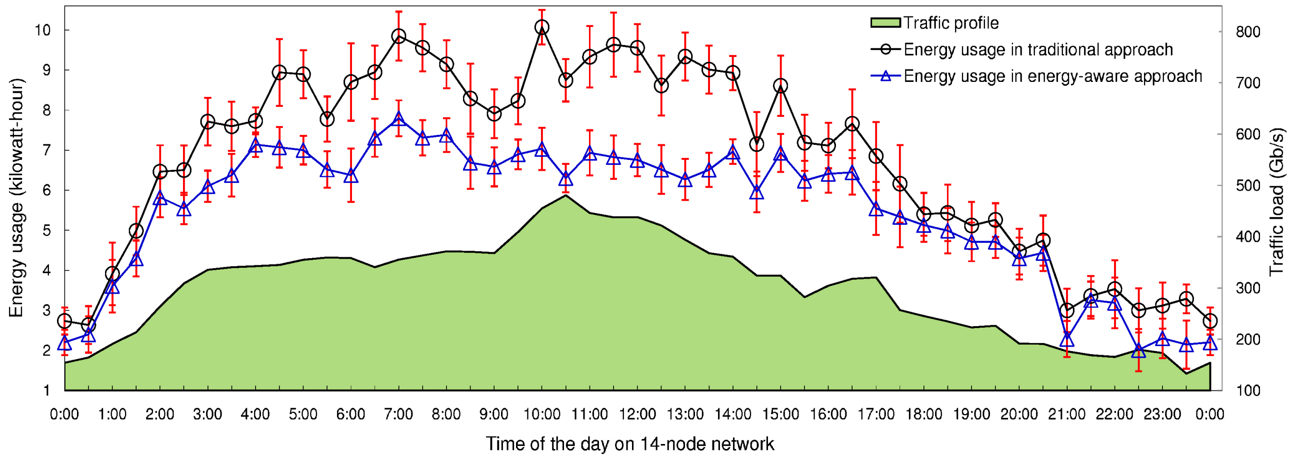

Fig. 17. Energy consumption in the 14-node network for the dynamic case.

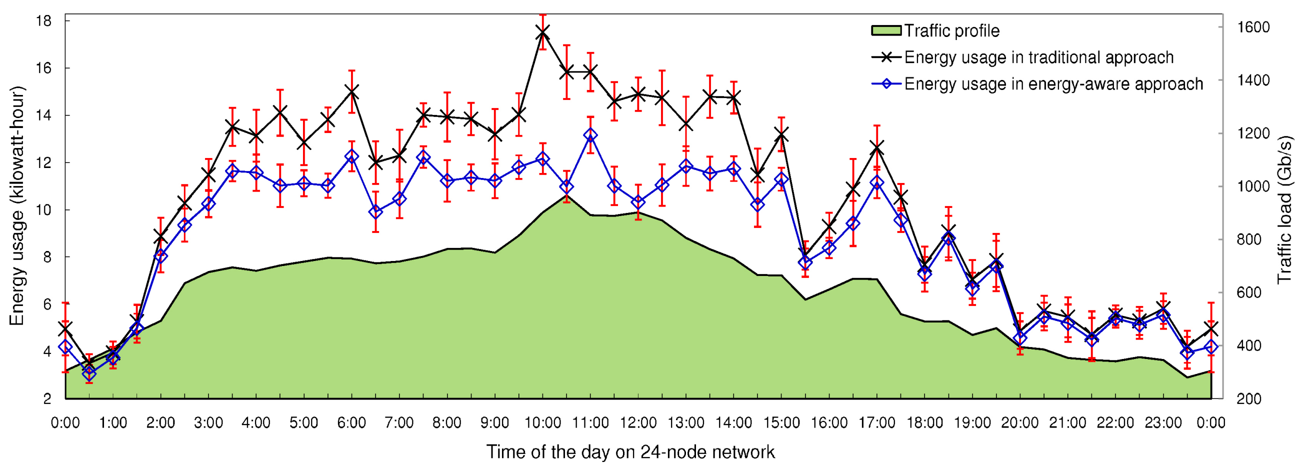

Fig. 18. Energy consumption in the 24-node network for the dynamic case.

for traditional case (as given in Table I) accordingly reflect the cost of wavelength-links. On the other hand, the RSB mode prioritizes total demand size among node-pairs, which is less reflected in the weight assignments for traditional case.

Both energy-aware schemes, however, exhibit more blocking than traditional schemes at high load, which is consistent with results found by other researchers [52], [53]. To analyze further, we observe lightpath length (i.e., average physical hop count of a lightpath) and wavelength-link usage (i.e., total number of wavelength-links used). For example, Fig. 14 shows lightpath lengths for RSB schemes in both networks. In energy-aware cases, a longer lightpath is required to maximize the re-use of already active components. As a result, the total wavelength-links used to satisfy requests are higher (as verified in Fig. 15). Due to the unavailability of wavelength-links at higher load, higher blocking is experienced. However, the average lightpath length is reduced as load increases for the energy-aware cases in both 14-node and 24-node networks. At low load, we follow longer paths to minimize active components, but at high load, longer paths with already active components are exhausted and shorter paths with idle components are initiated.

An interesting observation is made in Fig. 16, where the total number of transceivers used in allocating requests is drawn. At low load, both energy-aware and traditional cases require almost the same number of transceivers. At high load, a lower number of transceivers is needed for the energy-aware case since more requests are blocked in such a scenario.

C. Comparisons for the Dynamic Case

We study energy usage and other metrics for dynamic traffic grooming. As mentioned earlier, we take a traffic profile from a 10 GbE Atlanta-Houston connection in the Internet2 backbone network [51] and scale the traffic based on the network capacity under consideration. As shown in Fig. 17 for the 14-node network and Fig. 18 for the 24-node network, the total energy consumption is always lower in the proposed energy-aware approach than in the traditional approach. At off-peak hours of the day both approaches have fewer requests to be groomed and the energy saving is not significant. At peak hours of the day, the energy saving in the energy-aware approach is higher since more traffic requests are routed through already used (or activated) components by existing traffic. In the traditional case, requests that can not be groomed may or may not be routed through already activated components. This attribute is further illustrated in Fig. 19, which shows that the average physical length (or hop count) of a lightpath is indifferent to traffic pattern in the

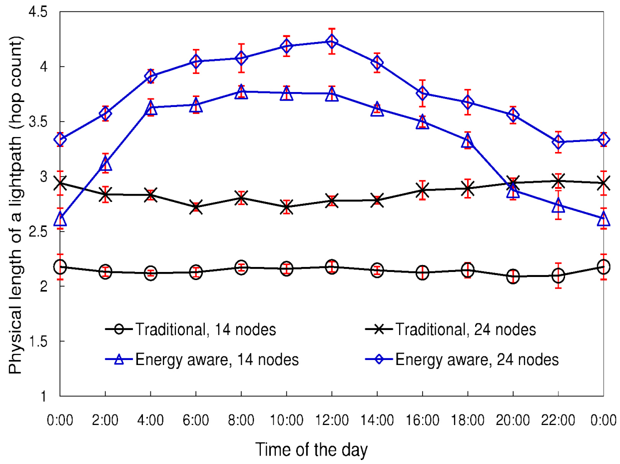

Fig. 19. Average length of lightpaths.

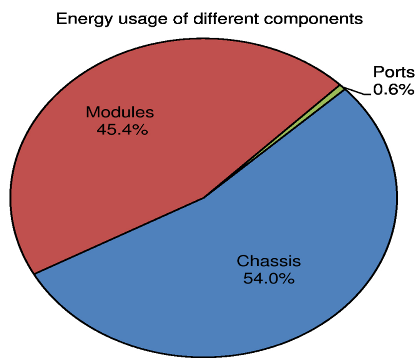

Fig. 20. Energy consumption by different components of a node.

traditional case. On the other hand, in the energy-aware case, the physical length of a lightpath is increased at peak hours since requests follow longer paths to be provisioned through already activated components. Consequently, we observe as much as 30% energy saving at peak hours. This observation is similar to the static case traffic grooming at approximately 30% network load since the total traffic at peak-hour of the day for dynamic case is similar to the total traffic in our simulation with static case at about 30% load. Like the static case, the bigger the network is, the more total energy (and money) can be saved in the dynamic case.

The distribution of energy expense among chassis, modules, and ports are shown in Fig. 20 for the 14-node network at 10:00 am. As expected, the dominant components are chassis (54% of energy expense) and modules (45.4% of energy expense). Since ports consume less energy, reducing total number of ports during routing may not generate desired energy conservation. Rather, the careful choice of ports during routing (i.e., locations of ports on modules and chassis) may generate substantial energy conservation via minimizing active modules and chassis. One may also reduce energy expense in a node by using more modules per chassis and more ports per module such that total number of active components are minimized. However, such an approach is not practical due to the impositions from physical characteristics (e.g., design modularity, scalability, and air cooling at the point of presence [17]).

V. Conclusion

In this paper, we investigated energy-aware traffic grooming problems for WDM optical networks. We assumed that switches are modular in terms of power management and operations. We considered both the static and dynamic traffic grooming, and formulated the the static problem in integer linear programming. We applied multiple heuristics over an AG model representing the relationship among modular physical architecture, lightpath level, and wavelength level.

The proposed energy-aware traffic grooming approach can save as much as 30% energy consumption in the network when compared with traffic grooming approaches lacking energy awareness for both the static case (specifically at nonblocking traffic load) and the dynamic case (specifically at peak-hour of the day when the traffic load is about 30% of the network capacity as in the static case). We found that the bigger the network is, the more energy saving is achievable. Given that networks are usually over-provisioned to the peak-hour traffic level and spend many hours at subcapacity of the network, the potential energy saving seems to be significant both in monetary and ecological points of view. Our future goals are to study the modular architecture in the electronic section of an optical node and to analyze different cost models.

References

[1] E. B. Desurvire, "Capacity demand and technology challenges for lightwave systems in the next two decades," *IEEE/OSA J. Lightw. Technol.*, vol. 24, no. 12, pp. 4697–4710, Dec. 2006.

[2] J. Baliga, K. Hinton, and R. S. Tucker, "Energy consumption of the internet," in *Proc. 32nd Australian Conf. Opt. Fibre Technol.*, Jun. 2007, pp. 1–3.

[3] J. Baliga, R. Ayre, K. Hinton, and R. S. Tucker, "Photonic switching and the energy bottleneck," in *Proc. IEEE Int. Conf. Photonics Switching*, Aug. 2007, pp. 125–126.

[4] G. Ananthanarayanan and R. H. Katz, "Greening the switch," in *Proc. Workshop Power Aware Comput. Syst. (HotPower), USENIX*, Dec. 2008, p. 7.

[5] S. Nedevschi, L. Popa, G. Iannaccone, S. Ratnasamy, and D. Wetherall, "Reducing network energy consumption via sleeping and rate-adaptation," in *Proc. 5th USENIX Symp. Networked Syst. Design Implementation*, Apr. 2008, pp. 323–336.

[6] IEEE P802.3az Energy Efficient Ethernet Task Force. (2011, Jul.) [Online]. Available: http://www.ieee802.org/3/az/index.html

[7] J. R. Vacca, *Optical Networking Best Practices Handbook*. New York: Wiley-Interscience, 2007.

[8] M. Minami and H. Morikawa, "Some open challenges for improving the energy efficiency of the internet," in *Proc. 3rd Int. Conf. Future Internet Technol.*, Jun. 2008, pp. 1–2.

[9] K. Christensen, C. Gunaratne, B. Nordman, and A. George, "The next frontier for communications networks: Power management," *Comput. Commun.*, vol. 27, no. 18, pp. 1758–1770, Dec. 2004.

[10] K. Christensen, B. Nordman, and R. Brown, "Power management in networked devices," *IEEE Comput.*, vol. 37, no. 8, pp. 91–93, Aug. 2004.

[11] Corning Inc.. (2011, Jan.). *The Green Advantage of 10G Optical Fiber* [Online]. Available: http://catalog2.corning.com/CorningCableSystems/media/ NAFTA/Marketing_Documents/LAN-1078-EN.pdf

[12] The U.S. Energy Information Administration (EIA). (2011, Jan.). *Electric Power Industry CO_2 Emissions and Generation Share by Fuel Type* [Online]. Available: http://www.eia.doe.gov/cneaf/electricity/page/co2_report/co2report.html

[13] M. Gupta and S. Singh, "Greening of the internet," in *Proc. ACM SIGCOMM*, Aug. 2003, pp. 19–26.

[14] M. Allman, K. Christensen, B. Nordman, and V. Paxson, "Enabling an energy-efficient future internet through selectively connected end systems," in *Proc. Sixth Workshop Hot Topics Netw. (HotNets-VI)*, Nov. 2007, pp. 1–7.

[15] C. Gunaratne, K. Christensen, and B. Nordman, "Managing energy consumption costs in desktop PCs and LAN switches with proxying, split TCP connections, and scaling of link speed," *Int. J. Netw. Manage.*, vol. 15, no. 5, pp. 297–310, Sep. 2005.

[16] C. Gunaratne, K. Christensen, B. Nordman, and S. Suen, "Reducing the energy consumption of ethernet with adaptive link rate (ALR)," *IEEE Trans. Comput.*, vol. 57, no. 4, pp. 448–461, Apr. 2008.

[17] J. Chabarek, J. Sommers, P. Barford, C. Estan, D. Tsiang, and S. Wright, "Power awareness in network design and routing," in *Proc. IEEE INFOCOM*, Apr. 2008, pp. 457–465.

[18] S. Nedevschi, S. Ratnasamy, and J. Padhye, "Hot data centers versus cool peers," in *Proc. Workshop Power Aware Comput. Syst.(HotPower)*, Dec. 2008, p. 8.

[19] M. M. Hasan, F. Farahmand, and J. P. Jue, "Traffic grooming for energy-aware optical networks," Dept. Computer Science, Univ. Texas, Dallas, TX, Tech. Rep. UTDCS-31-09, Sep. 2009.

[20] R. S. Tucker, "Optical packet switching: A reality check," *Optical Switching Networking,* , vol. 5, no. 1, pp. 2–9, 2008.

[21] R. S. Tucker, "The role of optics and electronics in high-capacity routers," *IEEE/OSA J. Lightw. Technol.*, vol. 24, no. 12, pp. 4655–4673, Dec. 2006.

[22] K. Hinton, P. M. Farrell, and R. S. Tucker, "The photonic bottleneck," in *Proc. IEEE/OSA Conf. OFC*, Mar. 2007, pp. 1–3.

[23] S. Aleksic, "Analysis of power consumption in future high-capacity network nodes," *IEEE/OSA J. Opt. Commun. Networking*, vol. 1, no. 3, pp. 245–258, Aug. 2009.

[24] Y. Zhang, P. Chowdhury, M. Tornatore, and B. Mukherjee, "Energy efficiency in telecom optical networks," *IEEE Commun. Surveys Tutorials*, vol. 12, no. 4, pp. 441–458, Nov. 2010.

[25] J. Baliga, R. Ayre, W. V. Sorin, K. Hinton, and R. S. Tucker, "Energy consumption in access networks," in *Proc. IEEE/OSA Conf. Opt. Fiber Commun.*, Feb. 2008, pp. 1–3.

[26] C. Lange and A. Gladisch, "On the energy consumption of FTTH access networks," in *Proc. IEEE/OSA Conf. Opt. Fiber Commun.*, Mar. 2009, pp. 1–3.

[27] F. Idzikowski, S. Orlowski, C. Raack, H. Woesner, and A. Wolisz, "Saving energy in IP-over-WDM networks by switching off line cards in low-demand scenarios," in *Proc. 14th Opt. Netw. Design Modeling Conf.*, 2010, pp. 1–6.

[28] C. Lange and A. Gladisch, "Energy efficiency limits of load adaptive networks," in *Proc. IEEE/OSA Conf. Opt. Fiber Commun.*, Mar. 2010, pp. 1–3.

[29] Y. Wu, L. Chiaraviglio, M. Mellia, and F. Neri, "Power-aware routing and wavelength assignment in optical networks," in *Proc. 35th Eur. Conf. Opt. Commun.*, Sep. 2009, pp. 1–2.

[30] L. Chiaraviglio, M. Mellia, and F. Neri, "Energy-aware networks: Reducing power consumption by switching off network elements," in *Proc. GTTI*, May 2008, pp. 1–6.

[31] L. Chiaraviglio, M. Mellia, and F. Neri, "Reducing power consumption in backbone networks," in *Proc. IEEE ICC*, Jun. 2009, pp. 1–6.

[32] L. Chiaraviglio, M. Mellia, and F. Neri, "Energy-aware backbone networks: A case study," in *Proc. IEEE Int. Workshop Green Commun.*, Jun. 2009, pp. 1–5.

[33] G. Shen and R. S. Tucker, "Energy-minimized design for IP over WDM networks," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 1, no. 1, pp. 176–186, Jun. 2009.

[34] P. Chowdhury, M. Tornatore, and B. Mukherjee, "On the energy efficiency of mixed-line-rate networks," in *Proc. IEEE/OSA Conf. Opt. Fiber Commun.*, Mar. 2010, pp. 1–3.

[35] A. Cianfrani, V. Eramo, M. Listanti, M. Marazza, and E. Vittorini, "An energy saving routing algorithm for a green OSPF protocol," in *Proc. IEEE INFOCOM*, Mar. 2010, pp. 1–5.

[36] S. Huang, D. Seshadri, and R. Dutta, "Traffic grooming: A changing role in green optical networks," in *Proc. IEEE GLOBECOM*, Nov. 2009, pp. 1–6.

[37] E. Yetginer and G. N. Rouskas, "Power efficient traffic grooming in optical WDM networks," in *Proc. IEEE GLOBECOM*, Nov. 2009, pp. 1–6.

[38] M. Xia, M. Tornatore, Y. Zhang, P. Chowdhury, C. Martel, and B. Mukherjee, "Greening the optical backbone network: A traffic engineering approach," in *Proc. IEEE ICC*, 2010, pp. 1–5.

[39] M. Xia, M. Tornatore, Y. Zhang, P. Chowdhury, C. Martel, and B. Mukherjee, "Green provisioning for optical WDM networks," *IEEE J. Selected Topics Quantum Electron.*, vol. 17, no. 2, pp. 1–9, Mar.–Apr. 2010.

[40] G. Schudel and D. J. Smith, "Chapter 1: Internet protocol operations fundamentals," in *Network World*. Indianapolis, IN: Cisco Press, Jan. 2008.

[41] *Cisco CRS-1 System*. (2011, Jan.) [Online]. Available: http://www.cisco.com/en/US/products/ps5842/index.html

[42] Cisco White Paper. (2011, Jan.). *Reduce Power Consumption Through Integrated Services Delivery* [Online]. Available: http://www.cisco.com/en/US/solutions/collateral/ns340/ns517/ns477/net_implementation_white_paper0900aecd80716af6.html

[43] *Cisco CRS-1 Series Carrier Routing System Getting Started Guide*, Cisco Document, Chapter 1, Release 2.0 [Online]. Available: http://www.cisco.com/en/US/docs/ios_xr_sw/iosxr_r2.0/getting_started/installation/guide/crsget_2.html

[44] *Cisco Power Calculator*. (2011, Jul.) [Online]. Available: http://tools.cisco.com/cpc

[45] B. Mukherjee, *Optical WDM Networks*. New York: Springer, Jan. 2006.

[46] C. Cavdar, A. Yayimli, and B. Mukherjee, "CATZ: Time-zone-aware bandwidth allocation in layer 1 VPNs," *IEEE Commun. Mag.*, vol. 45, no. 4, pp. 60–66, Apr. 2007.

[47] C. Cavdar, A. Yayimli, S. Rai, and B. Mukherjee, "Time-zone-aware traffic grooming in IP-over-WDM networks," in *Proc. IEEE High-Speed Netw. Workshop*, May 2007, pp. 31–35.

[48] H. Zhu, H. Zang, K. Zhu, and B. Mukherjee, "A novel generic graph model for traffic grooming in heterogeneous WDM mesh networks," *IEEE/ACM Trans. Network.*, vol. 11, no. 2, pp. 285–299, Apr. 2003.

[49] K. Zhu, H. Zang, and B. Mukherjee, "A comprehensive study on next-generation optical grooming switches," *IEEE J. Selected Areas Commun.*, vol. 21, no. 7, pp. 1173–1186, Sep. 2003.

[50] X. Huang, F. Farahmand, and J. P. Jue, "Multicast traffic grooming in wavelength-routed WDM mesh networks using dynamically changing light-trees," *IEEE/OSA J. Lightw. Technol.*, vol. 23, no. 10, pp. 3178–3187, Oct. 2005.

[51] Internet2 networking consortium. (2011, Jul.). *The Internet2 Network Observatory Data Views* [Online]. Available: http://www.internet2.edu/observatory/archive/data-views.html

[52] S. Zhang, D. Shen, and C.-K. Chan, "Energy-efficient traffic grooming in WDM networks with scheduled time traffic," *IEEE/OSA J. Lightw. Technol.*, vol. 29, no. 17, pp. 2577–2584, Sep. 2011.

[53] F. Farahmand, I. Cerutti, M. M. Hasan, and J. P. Jue, "Energy-efficiency of drop-and-continue traffic grooming," in *Proc. IEEE/OSA Conf. Opt. Fiber Commun.*, Mar 2011, pp. 1–3.

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Jason P. Jue, photograph and biography not available at the time of publication.

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