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

M. Masud Hasan, Farid Farahmand, Jason P. Jue, and Joel J. P. C. Rodrigues

Abstract—Compared to the research in energy-aware wireless and Ethernet networks, less attention has been given to energy-aware optical counterparts. 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. Since energy usage is an important element of operational expenditure (OPEX), 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 with simulation results.

Index Terms—Energy-Efficiency; Optical Networks; Traffic Grooming; Modular Switch Architecture.

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 hours 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 USA alone, the energy spent per year for network infrastructures is on the order of tera-watts, thus offering the potential of saving billions of dollar via energy-awareness [4], [9], [10]. Note that energy-awareness in network components provides savings in terms of not only electricity, but also other tangible operations and maintenance costs such as air-conditioning and diesel costs [7]. In addition to these economical rewards, there is an important ecological advantage of energy-awareness. An estimate by the USA Energy Information Administration (EIA) indicates that the generation of one kWh of electricity emits an average of 1.35 lbs of harmful CO₂ [12]. Given the tera-watt level energy spending for network infrastructures in the USA, reducing power consumption in networks is expected to reduce CO₂ 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.

A. Related Studies

A significant body of literatures 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 study is on intelligent protocols for wired optical networks.

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 10⁶ 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 (PONs), fiber to the node (FTTN), 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], [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 independence 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 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 study, 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 (DCSs). 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 equipments 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 sub-wavelength granularity, they are often groomed together in the nodes along their routes [45].

The main contribution of this study 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 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 the rest of the paper, Section II describes problem statements and a mathematical formulation, Section III discusses the construction of auxiliary graph and heuristic algorithms, Section IV presents simulation results, and Section V concludes the work.

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], [42]. The given parameters are:

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 sub-granular connections. In these contexts, we study both static and dynamic energy-aware traffic grooming problems as follows.

A. The Static Case

Given a set of sub-granular traffic requests (e.g., if \( C \) is \( OC-192 \), requests can be \( OC-1, OC-3, OC-12, \ldots, \) 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 traffic grooming formulations is available in [45]. Here, we present an Integer Linear Programming (ILP) formulation with respect to our problem.

- **Notations**
  - \( s, d \): 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

- **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
  - \( P^w_{mn} \): wavelength \( w \) on fiber \( P_{mn}, P^w_{mn} = P_{mn} \)
  - \( N^m \): number of chassis at node \( m \)
  - \( N^k_m \): number of modules at chassis \( k \) at node \( m \)
  - \( N^{lp}_m \): number of ports at module \( l \) of chassis \( k \) at node \( m \); index \( l \) is also used for index \( m \)
  - \( PT^{m,n,p} \): 1 if node pair \((m, n)\) is fiber-linked via port \( p \) of module \( l \) of chassis \( k \) at node \( m \), 0 otherwise
  - \( EA^{klp} \): energy consumption by port \( p \) of module \( l \) of chassis \( k \) at node \( m \) when it is active
  - \( EA^k \): energy consumption by module \( l \) of chassis \( k \) at node \( m \) when it is active
  - \( EA^k \): energy consumption by chassis \( k \) at node \( m \) when it is active
  - \( EI^m_{klp} \): energy consumption by port \( p \) of module \( l \) of chassis \( k \) at node \( m \) when it is idle
  - \( EI^m_k \): energy consumption by module \( l \) of chassis \( k \) at node \( m \) when it is idle
  - \( EI^m_k \): energy consumption by chassis \( k \) at node \( m \) when it is idle
  - \( A_{y,sd} \): number of \( OC-y \) connection requests between node \( s \) and node \( d \); here, \( y \in \{1, 3, 12, \ldots\} \)

- **Variables**
  - \( P^i_{mn,w} \): 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 \( V_{ji} \)
  - \( V^w_{ij} \): number of lightpaths from node \( i \) to node \( j \) on wavelength \( w \); here, \( V^w_{ij} \geq 1 \) implies multiple lightpaths taking different paths on wavelength \( w \)
  - \( A_{y,t,sd} \): the \( t^{th} \) \( OC-y \) request from node \( s \) to node \( d \) employing node-pair \((i, j)\) as an intermediate virtual link
  - \( S^w_{sd,t} \): 1 if the \( t^{th} \) \( OC-y \) request from node \( s \) to node \( d \) is successfully routed; 0 otherwise
  - \( PT^i \): total number of ports at node \( i \)
  - \( A^w_{klp} \): 1 if port \( p \) of module \( l \) of chassis \( k \) at node \( m \) is active (i.e., used by any lightpath), 0 otherwise
  - \( A^w_{k} \): 1 if module \( l \) of chassis \( k \) at node \( m \) is active (i.e., used by any lightpath), 0 otherwise

- **Constraints**
  - The total number of ports available at node \( i \) is the summation of ports in all modules of all chassis. That is,
    \[
    PT^i = \sum_k \sum_p N^p_k. \tag{1}
    \]
  - 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,
    \[
    V_{ij} = \sum_w V^w_{ij}. \tag{4}
    \]
  - To obey flow conservation in a node,
    \[
    \sum_m P^i_{mq,w} = \sum_m P^j_{qn,w}, \forall i, j, w, q \neq i, j. \tag{5}
    \]
    \[
    \sum_m P^i_{mq,w} = 0, \forall i, j, w, q. \tag{6}
    \]
    \[
    \sum_m P^j_{qn,w} = 0, \forall i, j, w. \tag{7}
    \]
  - 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, i.e.,
    \[
    \sum_m P^i_{mq,w} = V^w_{ij}, \forall i, j, w. \tag{8}
    \]
    \[
    \sum_m P^j_{mq,w} = V^w_{ij}, \forall i, j, w. \tag{9}
    \]
  - To prevent a wavelength \( w \) of a fiber \((m, n)\) being used by multiple virtual links,
    \[
    \sum_m P^i_{mq,w} = P^w_{mn}, \forall w. \tag{10}
    \]
  - On the virtual topology, flow conservation also holds true,
    \[
    \sum_l A^t_{y,sd} = S^t_{y,sd}, \forall s, d, y, t \in \{1, A_{y,sd}\}. \tag{11}
    \]
    \[
    \sum_l A^t_{y,sd} = S^t_{y,sd}, \forall s, d, y, t \in \{1, A_{y,sd}\}. \tag{12}
    \]
    \[
    \sum_l A^t_{y,sd} = 0, \forall s, d, y, t \in \{1, A_{y,sd}\}. \tag{13}
    \]
    \[
    \sum_l A^t_{y,sd} = 0, \forall s, d, y, t \in \{1, A_{y,sd}\}. \tag{14}
    \]
  - For the flow conservation of intermediate nodes,
B. The 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 study. We do not consider the “time-zone dynamism” as in [48]–[50].

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 auxiliary graph (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 corresponding AG is constructed in Fig. 2(c) that has three layers: 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 (GE) as marked in Fig. 2(c).

### 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,

$$
\text{maximize} \sum_{p} \left( A_{klp}^m \cdot E A_{klp}^m + (1 - A_{klp}^m) \cdot E T_{klp}^m \right)
$$

subject to constraints (1) to (23).

#### B. The 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 study. We do not consider the “time-zone dynamism” as in [46, 47].
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 (MxE). An edge from the input vertex of the lightpath layer to the input vertex of the access layer is a demultiplexing edge (DxE).

- **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 (TE). An edge from the input vertex of the chassis layer to the input vertex of the access layer is a receiver edge (RE).

- **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).

- **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).

- **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 each fiber has the same number of wavelengths). Such edges are called a wavelength-link edge (WLE). An edge between the port and wavelength layers is called a 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 Fig. 3 and Fig. 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 WLEs 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 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 $2 \times (2 + \text{(number of chassis, modules, and ports)}) + (W \times \text{node-degree})$. This number is a constant and, therefore, the auxiliary graph model remains tractable.

**Input:** A physical topology, a set of requests  
**Output:** A virtual topology with traffic grooming

**Pseudo-code:**
1. Let $L$ be the set of node pairs sorted by the total demand for traffic grooming (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 the capacity of a lightpath is less than the demand of $r$,
      5. Delete the lightpath from the AG.
   6. Find the shortest path $p$ from the access layer of $s$ to the input vertex of the access layer of $d$.
   7. If $p$ does not exist,
      8. Block request $r$.
10. Add the lightpaths deleted in step 5.
11. Let $L = L \setminus \{(s, d)\}$.
12. If $L$ is empty, go to line 2.

Fig. 5. Pseudo-code of the algorithm.

### 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 uses 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 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 new lightpath-links 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 watts, a line card/module is 315 watts, and a chassis is 375 watts (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.

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 2 chassis, 2 modules per chassis, and 2 ports per module. The 24-node network has 43 bidirectional links. Each node is assigned at most 3 chassis, 4 modules per chassis, and 4 ports per module. We assume that wavelength capacity is OC-192 and traffic requests are of sub-wavelength 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 dynamics. 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 $2 \times \text{number of links} \times \text{number of wavelengths per link} \times \text{wavelength capacity}$ and the load added to the network by a traffic request is measured by $\text{request size} \times \text{shortest hop distance}$.

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**Table I:** Weight Assignments of Edges in the Auxiliary Graph

<table>
<thead>
<tr>
<th>Edge Type</th>
<th>Energy-aware schemes</th>
<th>Other schemes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grooming edge</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Max/demux edge</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Transceiver edge</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Lightpath edge</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Chassis edge (idle)</td>
<td>400</td>
<td>0</td>
</tr>
<tr>
<td>Chassis edge (active)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Module edge (idle)</td>
<td>300</td>
<td>0</td>
</tr>
<tr>
<td>Module edge (active)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Port edge (idle)</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Port edge (active)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bypass edge</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wavelength-link edge</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

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Fig. 6. A network topology with 14 nodes and 21 links.

Fig. 7. A network topology with 24 nodes and 43 links.
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.

<table>
<thead>
<tr>
<th>Nodes</th>
<th>Schemes</th>
<th>Energy usage (kWh)</th>
<th>Cost (1000 US $)</th>
<th>Saving (1000 US $)</th>
<th>% of saving</th>
</tr>
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(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 request-size-based sorting in RSB leads better grooming (i.e., filling up wavelength-capacity more uniformly).

For the 24-node network, the total load varies 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 that total energy consumed is higher in the bigger network since more physical components are involved in the latter case.

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 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 watts/chassis, 315 watts/module, and 3 watts/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 scheme also exhibit similar behavior, with RSB approaches showing slightly better energy saving than LUB approaches. The reason is that request-size-based sorting in RSB leads better grooming (i.e., filling up wavelength-capacity more uniformly).

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 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 US dollars 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).

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 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 case 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 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 investigate energy-aware traffic grooming problems for WDM optical networks. We assume that switches are modular in terms of power management and operations. We consider both the static and dynamic traffic grooming, and formulate the the static problem in integer linear programming. We apply multiple heuristics over an auxiliary graph 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 non-blocking 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 find that the bigger is the network, the more energy saving is achievable. Given that networks are usually over-provisioned to the peak-hour traffic level and spend many hours at sub-capacity 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.

ACKNOWLEDGMENT
This work has been supported in part by the National Science Foundation (NSF), USA under CNS grant numbers 0916861 and 0627128.

REFERENCES


