Power Efficient Traffic Grooming in Optical WDM Networks

Emre Yetginer
Tubitak UEKAE
Ilhan Tan Kislasi
Umitkoy, Ankara 06800 Turkey
Email: emre.yetginer@iltaren.tubitak.gov.tr

George N. Rouskas
Department of Computer Science
North Carolina State University
Raleigh, NC 27695-8206 USA
Email: rouskas@ncsu.edu

***Abstract*—Power-awareness in networking attracts more attention as the trends in the energy consumption of the Internet raise growing concerns about the environmental impacts and sustainability of the network expansion. Building energy efficient equipment is definitely an integral part of the solution. However, such a strategy should be complemented with appropriate network protocols and routing methods to achieve maximum performance. In this paper, total power consumption of an optical WDM network is modeled in terms of the power consumed by individual lightpaths. The proposed model is then used to develop an ILP (Integer Linear Programming) formulation of the grooming problem. The exact solution of the formulation on a small network indicates that significant energy savings can be achieved with power efficient grooming.**

I. INTRODUCTION

The Internet has proven its scalability in terms of bandwidth, by evolving into a complex worldwide system as a result of the exponentially growing demand. However, this growth has been accompanied by an increase in both the number and power consumption of the network equipment, which raises concerns about the operational costs and environmental impacts of the Internet [1]–[4]. On the other hand, increasing power density threatens the downward trend of *power per byte transmitted*, which has been a driving force behind the expansion of the network [5]. Hence, the new question turns out to be the scalability of Internet in terms of power consumption. And improving the efficiency of the network emerges as an important part of the answer.

In addition to building energy efficiency into the networking hardware and protocols, power aware routing and traffic engineering approaches may also help to improve the power consumption of the communications infrastructure. In that respect, traffic grooming seems to be a suitable candidate. Traffic grooming addresses the gap between the capacity of wavelength channels and bandwidth requirements of individual connections in wavelength routed WDM networks. The physical topology of a WDM network consists of a set of optical cross connect (OXC) nodes connected by fiber links. A virtual topology is constructed by connecting OXCs using wavelength paths, called *lightpaths*, which may span several fiber links. The connections are routed over the virtual topology, possibly traversing a sequence of lightpaths from source to destination. However, the bandwidth of connections is usually small compared to the capacity of wavelength channels, and this gives rise to the need for effectively packing the sub-wavelength granularity connections into the available lightpaths or so called *grooming.*

The grooming problem is extensively studied in the literature. Basic ILP (Integer Linear Programming) formulations are provided in [6] and [7]. Most of the grooming studies concentrated on either minimization of the total network cost (e.g., [8]), or maximization of the total revenue by satisfying as many demands as possible (e.g., [7]). [9] considers the minimization of number of transceivers, which is also equivalent to minimizing the number of lightpaths. A different approach is used in [10], where the aim is to minimize the electronic routing. In this paper, we study the grooming problem from a power consumption perspective and develop a formulation which effectively combines the objectives of minimizing the number of lightpaths and electronically routed traffic.

Energy consumption has been an important issue for wireless networks due to scarce energy sources [11]. However, for wire-line networks there are a limited number of studies. For Ethernet networks, Adaptive Link Rate (ALR) is proposed to improve the energy efficiency by dynamically decreasing the link capacity during low utilization periods [12]. [2] suggests the idea of putting components in network devices into sleep (energy saving mode) to increase the energy conservation in Internet. Both uncoordinated and coordinated sleeping models are considered. In uncoordinated sleeping, each router or switch makes its own sleeping decision. In coordinated sleeping, the routers collectively decide which interfaces to put to sleep. [5] proposes power-aware routing, which is similar to the notion of coordinated sleeping, to minimize the network-wide power consumption by adjusting routes on relatively coarse time scales. Recently, [13] discusses the idea of using traffic grooming for green optical networking. They develop both flow-based and interface-based formulations of power consumption and propose a heuristic for solving the latter formulation.

In this paper, the potential benefits of a power efficient grooming strategy are explored. Total power consumption of

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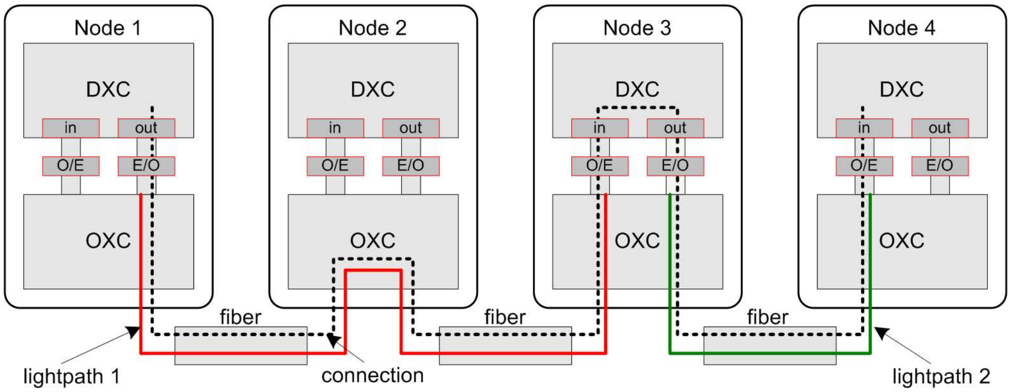

Fig. 1. Illustration of an optical WDM network and grooming

the network is formulated in terms of the power consumptions of individual lightpaths. This approach leads to a useful representation of the total power consumption as a function of the number of lightpaths and total amount of electronically switched traffic. The corresponding optimization problem is expressed as an ILP, which effectively combines and generalizes the two existing approaches to the grooming problem: minimization of number of lightpaths and minimization of electronically routed traffic. The potential benefits of the proposed approach is illustrated on a small sized network.

The rest of the paper is organized as follows. In Section II, the network power consumption model is discussed. Based on this model, the ILP formulations are introduced in Section III. Section IV presents the numerical results obtained on a sample network, and Section V concludes the paper.

II. NETWORK POWER CONSUMPTION MODEL

The operation of a wavelength routed WDM network is illustrated in Fig. 1 [14]. Each node is equipped with a DXC (Digital Cross Connect) and an OXC (Optical Cross Connect). The traffic from node 1 to node 4 is carried over the connection shown as a dashed line. The connection uses two lightpaths: one from node 1 to node 3, and the other one from node 3 to node 4. Lightpath 1 is optically switched at node 2, whereas the traffic is electronically switched between the two lightpaths at node 3.

It is assumed that, most of the network power is consumed at the DXC ports connected to the OXC, and in the transceivers which perform the O/E and E/O conversion. This is justified by the fact that, in distributed switch fabric systems, actual switching of traffic is performed on the line cards and most of the packet processing is done in input and output ports of the router. O/E and E/O conversions also require costly processing. Compared to electronic packet processing, optical domain processing demands much less power. This fact is justified by the advertised power consumption values of several commercial networking equipment. For example, Juniper Core Router T640 supports 8 ports, each at 40 Gbps and consumes 4500 W, which corresponds to a power consumption of 550 W per port [15]. On the other, Calient DiamondWave PXC 128 is an 128 by 128 port optical switch which consumes less than 750 W, or equivalently 6 W per port [16]. Therefore, the model developed in this section concentrates on the power consumed at DXC ports which are connected to the OXC and O/E/O converters. The power consumed at the local ports of the DXC that are connected to the access networks are not considered, since the same amount of traffic has to be added/dropped at these ports irrespective of the grooming solution.

Measurement studies have show that network equipment consume a considerable amount of power even without a traffic flow [5]. Hence, the power consumption of each component type, c, is divided into two terms: a fixed term independent of traffic and traffic dependent term as

$$P^c = P_0^c + P_t^c(t),$$

where t is the amount of traffic passing through the component. The power consumed in most types of the switching architectures has a linear dependence on traffic [17], [18]. Based on this fact and for the sake of simplicity, the traffic dependent power term, $P_t^c(t)$ is approximated as a linear function of t and P^c is written as

$$P^c = P_0^c + p^c \times t,$$

where p^c is effectively the marginal power consumption of the port per additional traffic unit. So, for each component the power consumption can be expressed as

$$\begin{aligned} P^{in} &= P_0^{in} + p^{in} \times t \\ P^{out} &= P_0^{out} + p^{out} \times t \\ P^{eo} &= P_0^{eo} + p^{eo} \times t \\ P^{oe} &= P_0^{oe} + p^{oe} \times t \end{aligned}$$

where P^{in}, P^{out}, P^{eo}, and P^{oe} are the power consumption at the input port and output port of the DXC, E/O converter and O/E converter, respectively.

It is assumed that inactive ports and transceivers can be shut down to save power. Denoting the set of all lightpaths as $\mathcal{LP}$, the set of lightpaths that originate at node n as $\mathcal{LP}_n^+$, and the set of lightpaths that terminate at node n as $\mathcal{LP}_n^-$, the total

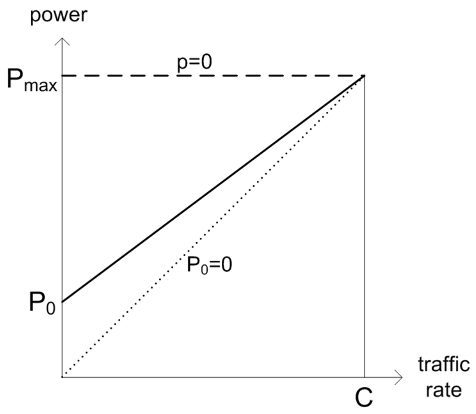

Fig. 2. Power consumed by a lightpath as a function of carried traffic

power consumption of node n can be written as

$$P_n = \sum_{lp \in \mathcal{LP}_n^-} \left(P_0^{in} + P_0^{oe} + t_{lp} \times (p^{in} + p^{oe})\right) + \sum_{lp \in \mathcal{LP}_n^+} \left(P_0^{out} + P_0^{eo} + t_{lp} \times (p^{out} + p^{oe})\right),$$

where t_{lp} is the amount of traffic carried on lightpath lp.

Total power consumed in the network is simply the sum of the power consumption of each node:

$$P_{total} = \sum_{n \in \mathcal{N}} P_n,$$

where $\mathcal{N}$ is the set of nodes in the network.

Since, each lightpath originates from and terminates at a single node, P_{total} can also be expressed as

$$P_{total} = \sum_{lp \in \mathcal{LP}} (P_0 + t_{lp} \times p), \tag{1}$$

where $P_0 = P_0^{in} + P_0^{oe} + P_0^{out} + P_s^{eo}$ corresponds to the traffic independent power consumption of a lightpath, and $p = p^{in} + p^{oe} + p^{in} + p^{oe}$ is the additional power consumed for each traffic unit carried.

The maximum power consumption of a lightpath is, $P_{max} = P_0 + C \times p$, where C denotes the capacity of a wavelength channel. The resulting lightpath power consumption curve is shown in Fig. 2 as the solid line.

In the ideal case of maximum efficiency at each traffic rate, $P_0 = 0$ and the dotted curve in Fig. 2 is obtained. That is, the power consumed by a lightpath is proportional to the traffic it carries. In that case, minimum total power is consumed when the sum of the traffic carried on all lightpaths is minimized, or equivalently when the amount of electronically routed traffic in the network is minimized. On the other hand, if the power consumption is independent of t (i.e., $p_{lp} = 0$ and $P_{max} = P_0$) as shown with dashed line in Fig. 2, then the total power consumed in the network depends only on the number of lightpaths. Hence, minimizing the number of lightpaths yields the minimum power consumption.

Rearranging the terms in (1) yields

$$P_{total} = |\mathcal{LP}| \times P_0 + p \times \sum_{lp \in \mathcal{LP}} t_{lp}, \tag{2}$$

which states that the power consumption of the network is a weighted sum of the number of lightpaths and total amount of traffic electronically routed. In the following section, the ILP formulation for power efficient grooming is developed based on (2).

III. ILP FORMULATION OF THE GROOMING PROBLEM

The physical topology of the optical network can be represented as a graph $G = (\mathcal{N}, \mathcal{L})$, where $\mathcal{N}$ is the set of network nodes and $\mathcal{L}$ is the set of physical links connecting the nodes. It is assumed that each physical link is directed and composed of a single fiber supporting W wavelength channels. The nodes are connected to each other by a couple of links in opposite directions. The bandwidth of a wavelength channel is measured as multiples of a basic traffic rate and denoted by C. The amount of traffic demand from node s to node d, in terms of the same basic rate is an integer and represented as t^{sd}. Hence, $T = [t^{sd}]$ forms the overall network traffic matrix.

The set of all node pairs in the network is denoted as $\mathcal{Z}$, i.e., $\mathcal{Z} = \{(n, m) : n, m \in \mathcal{N}, n \neq m\}$. $\mathcal{L}_i^+$ and $\mathcal{L}_i^-$ are defined as the set of outgoing and incoming links, respectively, at node i. The decision variables in the ILP formulation are defined as:

- b_{ij}: number of lightpaths from node i to node j
- b_{ij}^l: number of lightpaths from node i to node j which traverse link l
- $c_{ij}^{l,w}$ is 1 if a lightpath from node i to node j uses wavelength w on link l, 0 otherwise.
- t_{ij}^{sd}: amount of traffic from node s to node d carried on lightpaths from node i to node j

The objective functions and the constraints for the grooming formulation are explained in the following sections,.

A. Objective functions

Three different objective functions are used with the same set of constraints to obtain optimum grooming solutions, as described below.

1) Minimum Number of Active Router Ports : This is the most commonly used objective function in the literature [6], [9]. Noticing that each lightpath in the network is necessarily terminated at an electronic router interface, the number of active ports is twice the number of lightpaths in the network. Therefore, minimum number of active router ports can be obtained by minimizing the number of lightpaths established. The corresponding objective function is given by

$$L_{min} = \min \sum_{(i,j) \in \mathcal{Z}} b_{ij} \tag{3}$$

2) Minimum Amount of Electronically Switched Traffic: This is the objective function considered in [10]. The traffic carried by any lightpath in the network is terminated either at the destination node, or at an intermediate node where it may be groomed with other traffic and multiplexed into a new lightpath. So, the amount of traffic that is electronically switched in the network can be calculated as the difference between the total traffic carried by all lightpaths and the sum of the traffic demands for each source-destination pair, t^{sd}. Accordingly, the objective function can be written as

$$T_{min} = \min \sum_{(i,j)\in\mathcal{Z}} \sum_{(s,d)\in\mathcal{Z}} t_{ij}^{sd} - \sum_{(s,d)\in\mathcal{Z}} t^{sd} \tag{4}$$

3) Minimum Power Consumption: Based on the network power model developed in Section II, the following objective function is proposed to minimize the total power consumption.

$$P_{min} = \min P_0 \sum_{(i,j)\in\mathcal{Z}} b_{ij} + p \sum_{(i,j)\in\mathcal{Z}} \sum_{(s,d)\in\mathcal{Z}} t_{ij}^{sd} \tag{5}$$

This objective is a generalization of (3) and (4), in the sense that when the power consumption of lightpaths is independent of traffic (i.e., $p = 0$), then (5) reduces to (3). On the other hand, if the constant power consumption term, $P_0 = 0$, then (5) is equivalent to (4).

B. Constraints

Lightpath Routing Consraints:

$$\sum_{l\in\mathcal{L}_n^+} b_{ij}^l - \sum_{l\in\mathcal{L}_n^-} b_{ij}^l = 0 \qquad \forall n \in \mathcal{N}\backslash\{i,j\}, (i,j) \in \mathcal{Z} \tag{6}$$

$$\sum_{l\in\mathcal{L}_i^+} b_{ij}^l = b_{ij} \qquad \forall (i,j) \in \mathcal{Z} \tag{7}$$

$$\sum_{l\in\mathcal{L}_i^-} b_{ij}^l = 0 \qquad \forall (i,j) \in \mathcal{Z} \tag{8}$$

$$\sum_{l\in\mathcal{L}_j^+} b_{ij}^l = 0 \qquad \forall (i,j) \in \mathcal{Z} \tag{9}$$

$$\sum_{l\in\mathcal{L}_j^-} b_{ij}^l = b_{ij} \qquad \forall (i,j) \in \mathcal{Z} \tag{10}$$

Equations (6)-(10) are the lightpath routing constraints expressed as multi-commodity flow equations, where the lightpaths between a pair of nodes correspond to a single commodity. Equation (6) ensures that, at any intermediate node the number of incoming lightpaths is equal to the number of outgoing lightpaths. Equations (7)-(8) and (9)-(10) are the corresponding constraints for the origin and termination nodes of lightpaths.

Lightpath Wavelength Assignment Constraints:

$$\sum_{w} c_{ij}^{w,l} = b_{ij}^l \qquad \forall (i,j) \in \mathcal{Z}, l \in \mathcal{L} \tag{11}$$

$$\sum_{(i,j)\in\mathcal{Z}} c_{ij}^{w,l} \leq 1 \qquad \forall w, l \in \mathcal{L} \tag{12}$$

$$\sum_{l\in\mathcal{L}_n^+} c_{ij}^{w,l} - \sum_{l\in\mathcal{L}_n^-} c_{ij}^{w,l} = 0 \quad \forall n \in \mathcal{N}\backslash\{i,j\}, (i,j) \in \mathcal{Z}, w \tag{13}$$

$$\sum_{l\in\mathcal{L}_i^+} c_{ij}^{w,l} \leq b_{ij} \qquad \forall (i,j) \in \mathcal{Z}, w \tag{14}$$

$$\sum_{l\in\mathcal{L}_i^-} c_{ij}^{w,l} = 0 \qquad \forall (i,j) \in \mathcal{Z}, w \tag{15}$$

$$\sum_{l\in\mathcal{L}_j^+} c_{ij}^{w,l} = 0 \qquad \forall (i,j) \in \mathcal{Z}, w \tag{16}$$

$$\sum_{l\in\mathcal{L}_j^-} c_{ij}^{w,l} \leq b_{ij} \qquad \forall (i,j) \in \mathcal{Z}, w \tag{17}$$

Equations (11)-(17) are the lightpath wavelength assignment constraints. Equation (11) ensures that, each lightpath is assigned a wavelength on each link, and (12) ensures that, each wavelength is used at most once on each link. The wavelength continuity constraints are also expressed as multi-commodity flow equations in (13)-(17), where each wavelength for each lightpath between an origin and destination pair is treated as a separate commodity. Note that, (14) and (17) are already implied by constraints (7), (10) and (11). However, they are included for the sake of completeness.

Traffic Routing Constraints:

$$\sum_{(s,d)\in\mathcal{Z}} t_{ij}^{sd} \leq b_{ij} C \qquad \forall (i,j) \in \mathcal{Z} \tag{18}$$

$$\sum_{(s,d)\in\mathcal{Z}} t_{ij}^{sd} \geq b_{ij}(C-1) \qquad \forall (i,j) \in \mathcal{Z} \tag{19}$$

$$\sum_{j\in\mathcal{N}\backslash\{i\}} t_{ij}^{sd} - \sum_{j\in\mathcal{N}\backslash\{i\}} t_{ij}^{sd} = 0 \; \forall i \in \mathcal{N}\backslash\{s,d\}, (s,d) \in \mathcal{Z} \tag{20}$$

$$\sum_{j\in\mathcal{N}\backslash\{s\}} t_{sj}^{sd} = t^{sd} \qquad \forall (s,d) \in \mathcal{Z} \tag{21}$$

$$\sum_{j\in\mathcal{N}\backslash\{s\}} t_{js}^{sd} = 0 \qquad \forall (s,d) \in \mathcal{Z} \tag{22}$$

$$\sum_{j\in\mathcal{N}\backslash\{d\}} t_{dj}^{sd} = 0 \qquad \forall (s,d) \in \mathcal{Z} \tag{23}$$

$$\sum_{j\in\mathcal{N}\backslash\{d\}} t_{jd}^{sd} = t^{sd} \qquad \forall (s,d) \in \mathcal{Z} \tag{24}$$

Finally, (18)-(24) are the constraints for the routing of traffic over the virtual topology. Equation (18) is the wavelength channel capacity constraint, and (19) ensures that, just enough number of lightpaths are established between each origin-termination node. In other words, it prevents the establishment of idle lightpaths which do not carry traffic.

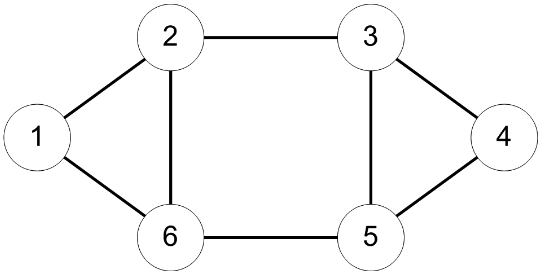

Fig. 3. Sample network used to compare grooming methods

IV. NUMERICAL RESULTS

Solution of the ILP formulation with the objective functions presented in section III-A results in three different traffic grooming strategies: $minL$, which minimizes the number of lightpaths or equivalently number of active router ports, $minT$ which minimizes amount of electronically switched traffic at intermediate nodes, and $minP$, which consumes the minimum power. In this section, these strategies are compared on a sample network to assess the trade-offs between them and potential power savings that can be achieved with power-aware grooming solution of $minP$.

It is well known that the grooming problem is NP-complete [7] and solvable for only small networks. Therefore, optimum grooming solutions are obtained for the sample network shown in Fig. 3. The network has $N = 6$ nodes (connected to each other with a couple of directed links in opposite directions), and a total of $L = 16$ links. Each link consists of a single fiber which supports $W = 3$ wavelength channels, each with capacity $C = 48$. Traffic demand for each node pair (s, d), t^{sd}, is a random integer uniformly distributed in $[0, t_{max}]$. The parameter t_{max} is changed to obtain results for different traffic loads. The fixed power consumption of a lightpath, P_0, is taken to be 0.25, whereas the maximum power consumed by a lightpath, P_{max}, is assumed to be 1.

Fig. 4 plots the number of lightpaths used by each grooming method as t_{max} is increased with steps of 2 units until 58, beyond which no feasible solution exists. As expected, $minL$ uses the minimum number of lightpaths. However, the number of lightpaths used by $minP$ is very close to $minL$ at each value of t_{max}. More specifically, the difference is at most 3 lightpaths and less than 3 for most of the t_{max} values. On the other hand, $minT$ uses much higher number of lightpaths. Indeed, for $t_{max} = 2$, separate lightpaths are established between each source and destination node pair, which effectively corresponds to a non-grooming solution. As the traffic load increases, the number of lightpaths used by $minP$ and $minL$ increase almost linearly due to the wavelength channel capacity constraint.

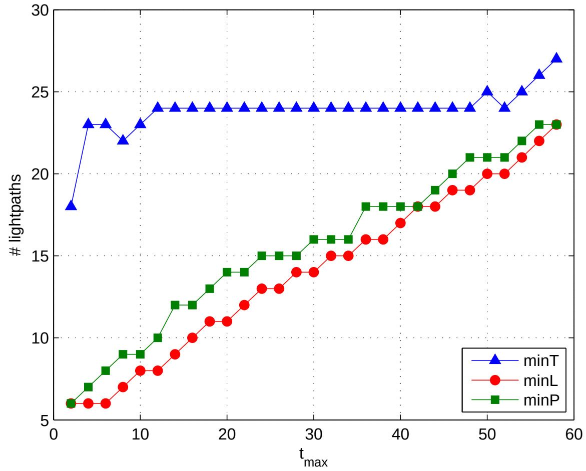

Fig. 4. Number of lightpaths used by each grooming method

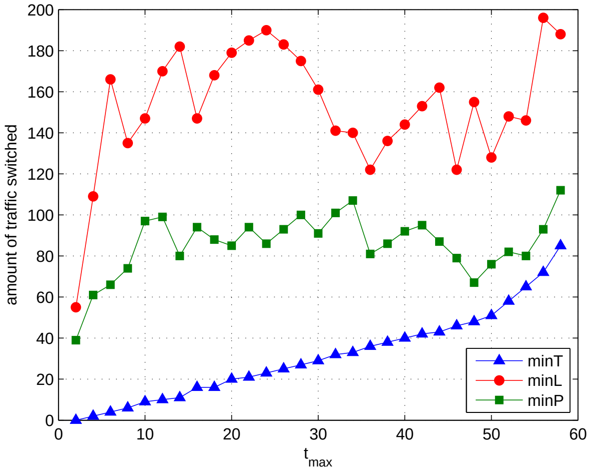

Fig. 5. Amount of electronically routed traffic by the grooming methods

The amount of traffic switched at intermediate nodes for each grooming method is shown in Fig. 5. It is observed that $minT$ achieves very low traffic switching levels at the cost of a much higher number of lightpaths. It sets up direct lightpaths between source-destination node pairs as much as possible. On the contrary, to minimize the number of lightpaths, $minL$ requires very high levels of switched traffic. A moderate amount of traffic is switched with $minP$ at each t_{max} and the difference between $minP$ and $minT$ vanishes as the network load is increased. Comparing $minP$ with $minL$, it is possible to state that $minP$ manages to decrease the amount of switched traffic nearly into half by using at most 3 more lightpaths.

Finally, the power consumed by each grooming solution is compared in Fig.6. The y-axis shows the amount of excess power consumption with respect to $minP$ as percentages. More clearly, at each t_{max} the normalized power consumption for $minL$ and $minT$ are obtained using

$$NP = 100 \times \frac{P - P^*}{P^*},$$

where P is the power consumption of the corresponding grooming method, and P^* is the optimum power consumption of $minP$.

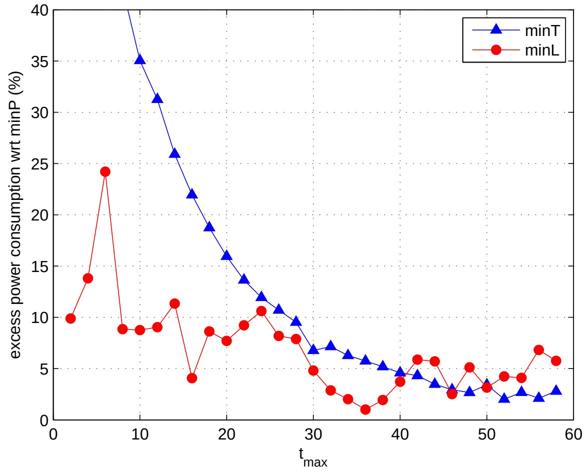

Fig. 6. Excess power consumption of $minL$ and $minT$ w.r.t. $minP$

For low values of t_{max}, the power consumption of $minT$ is much higher than $minP$. For $t_{max} = 2$, $minT$ consumes 95% more power than $minP$ (not shown in the figure). This can be explained by the fact that, for low traffic loads, $minT$ establishes unnecessarily high number of lightpaths which are clearly underutilized, and the power overhead of lightpaths (P_0) dominates the total power consumption. For this same reason, $minL$ performs better than $minT$ at low traffic loads. However, as t_{max} increases, all the grooming methods use nearly maximum possible number of lightpaths that can be established using the available wavelengths. In that case, amount of electronically routed traffic differentiates the relative power consumption, and $minT$ performs better than $minL$. It is also observed that for low traffic loads, $minL$ consumes 10%–25% more power than $minP$, and for moderate loads, the excess power consumption is 10% on the average.

These results suggest that, minimizing the number of lightpaths or amount of traffic switched alone may be inefficient in terms of overall power consumption even for a small network, and a power-aware grooming strategy may help reduce the power consumption of optical networks significantly for low to moderate traffic loads, which is actually the operating regime for most of the today's real world networks.

V. CONCLUSION

Power awareness in routing is a promising approach to improve the overall energy efficiency of communication networks. In this paper, the potential benefits of traffic grooming in decreasing the power consumption of an optical WDM network are explored. For this aim, a network power model is developed which relates the total power consumption to the power consumption of individual lightpaths. Based on this model a grooming formulation is presented. The results obtained on a small network suggest that power efficient grooming can lead to significant energy savings. A natural extension of this work is the development of heuristic methods for obtaining power efficient grooming solutions for larger networks, which is the subject of ongoing study.

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