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Energy-Aware Path Selection for Scheduled Lightpaths in IP-over-WDM Networks

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Abstract—Traffic grooming, i.e. the aggregation of multiple traffic streams on one channel or wavelength, has often been considered in the context of reducing blocking and improving capacity utilization. More recently, traffic grooming has also been advocated in the context of energy-aware routing. In this paper we study energy-efficient path selection under the scheduled traffic model in IP-over-WDM optical networks. We show that there is indeed a strong relation between traffic grooming and energy efficiency, but also that it sometimes pays off not to groom. We propose an energy-aware routing algorithm that is based on traffic grooming, but which has the flexibility to deviate from it where needed. Our approach can be applied to networks with and without wavelength conversion. Simulations show that our energy-aware routing algorithm both brings significant energy savings as well as a lower blocking probability in comparison to a shortest paths based routing algorithm and a traffic grooming algorithm.

I. INTRODUCTION

In wavelength division multiplexing (WDM) technology, the capacity of a fiber is divided into several non-overlapping wavelength channels that can transport data independently. These wavelength channels make up lightpaths that are used to establish optical connections that may span several fiber links. With current commercial technology, each lightpath can be independently operated at data rates of several Gb/s. However, traffic between a pair of nodes may not be able to fill up the available bandwidth of a lightpath. In order to efficiently utilize the available bandwidth, several independent traffic streams can be aggregated to share the capacity of a lightpath. This is known as traffic grooming (e.g., see [1]). While traffic grooming has obvious potential to increase throughput, the grooming of traffic may also lead to energy efficiency, although this is not always the case. The main contributions of this paper are (1) a model for energy consumption in IP-over-WDM networks, (2) an energy-aware algorithm, for allocating scheduled lightpaths, that finds the best balance between traffic grooming or setting up a new lightpath, and (3) a simulative study to the effect of introducing wavelength conversion on the overall blocking probability and consumed energy.

The remainder of this paper is organized as follows. Section II presents related work. Section III describes our network model and analyzes the energy consumption with traffic grooming and when setting up a new lightpath. An energy-aware routing algorithm for dynamic traffic is proposed in Section IV. Dynamic traffic refers to requests that come in an

on-line fashion, while for static traffic all requests are assumed to be known a priori. Section V provides our simulation results and Section VI concludes the paper.

II. RELATED WORK

Cavdar [2] addresses dynamic energy-aware traffic provisioning at the WDM layer by allocating weights to links and selecting a path with minimum weight. However, the author assumes that the capacity of each traffic demand is equal to the maximum capacity of each wavelength, which means that traffic grooming cannot be applied.

Xia *et al.* [7] discuss the energy and traffic flow details of every operation in an IP-over-WDM network. They subsequently propose an energy-aware routing algorithm that uses an auxiliary graph to represent the consumption of each operation, both at the IP and WDM layers. The proposed routing method can deal with both static and dynamic traffic, although for dynamic traffic an infinite holding time is assumed. Chen and Jaekel [3] do take holding time into account and use an ILP to show that the holding time affects the energy consumption in traffic grooming. However, they do not propose a scalable energy-efficient traffic grooming algorithm for scheduled traffic.

Zhang *et al.* [9] incorporate holding time in energy-aware traffic grooming and solve both the static and dynamic case. For static traffic, they propose an ILP. For dynamic traffic, they find the shortest paths in an auxiliary graph with specific weights. Their algorithm is compared to two routing algorithms from [10], which are “minimum lightpaths” that tries to minimize the number of newly established lightpaths and “minimum hops” that tries to minimize the number of lightpath hops. Simulation results show that the algorithm of Zhang *et al.* performs best under low traffic, but performs worst under high traffic.

The algorithm proposed in this paper uses a more refined energy model than in [9]. For instance, we distinct between energy consumed in router ports at the IP layer and in the components at the optical layer that consume a fixed energy for each full wavelength connection.

III. NETWORK MODEL AND ENERGY ANALYSIS

A. Network Architecture

We adopt the transparent IP-over-WDM with optical bypass and grooming model of Musumeci *et al.* [6]. It is a two-layered network architecture, with routers in the IP layer and optical cross connects (OXCs) in the WDM layer. The following components consume energy, where the values are taken from [6]:

- 1) Transponders ($E_{tr} = 34.5$ W per 10 Gb/s wavelength): Transponders have two functionalities: (i) O/E and E/O conversion between OXC and IP and (ii) transmitting and receiving signals.
- 2) OXCs ($E_{os} = 1.5$ W per 10 Gb/s wavelength): Optical cross connects optically switch traffic, either when traffic is bypassed at a node or when adding/dropping traffic.
- 3) Router ports ($E_{es} = 14.5$ W per Gb/s): The ports mainly deal with electronic processing.

We are only interested in the energy consumption involved in accommodating a new request. We therefore do not consider energy that is consumed continuously, irrespective of whether there is traffic or not. For instance, optical amplifiers consume a constant value of energy regardless of the presence of traffic. When our objective would be to switch off components, then those static energy costs would have to be taken into account.

B. Energy Analysis of Traffic Flow in Different Cases

We will discuss the energy model that we adopt in this paper and analyze the energy consumption in the cases of both traffic grooming and setting up a new lightpath.

Often, e.g. in [8], [5], [7], it is assumed that energy consumption P has the following linear relationship with traffic:

$$P = P_0 + P_t * T \quad (1)$$

where P_0 is the overhead which represents the idle energy consumption, P_t symbolizes the traffic-dependent energy factor, and T represents the amount of traffic in Gb. We consider different energy calculation methods for different operations. Some operations are only wavelength (but not traffic) dependent, in which case $P_t = 0$. For instance, once transponders and OXCs are switched on they will consume a fixed amount of energy corresponding to a full wavelength capacity (and not to the fraction of traffic transported).

$$P = \begin{cases} 34.5 \text{ W}/\lambda \quad \forall \text{ transponders} \\ 1.5 \text{ W}/\lambda \quad \forall \text{ OXCs} \end{cases} \quad (2)$$

For electronic switching (processing) at the IP layer, the energy consumption is traffic dependent.

$$P = 14.5 * T \quad \forall \text{ router ports} \quad (3)$$

Although in reality $P_0 \neq 0$, we have discarded its contribution (i.e., set $P_0 = 0$), since - like optical amplifiers - the router ports (currently) cannot be automatically switched on/off, and hence their energy consumption is always fixed.

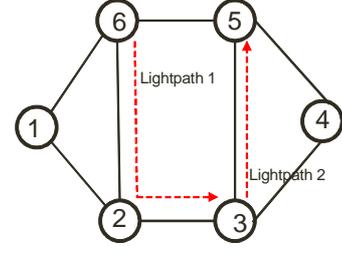


Fig. 1. Example

Let us consider the example of setting up a new lightpath in the network of Fig. 1, where already two lightpaths (6–2–3) and (3–5) exist. Lightpath 1 still remains for 5 hours and lightpath 2 remains for 6 hours. The new request $T(6, 5, b, 3 : 00, 4)$ asks for a lightpath from node 6 to node 5, needing b Gb/s, starting at time 3 : 00 and lasting for 4 hours. We discuss the energy consumption of two routing strategies to route this request: (i) making use of existing lightpaths, i.e. grooming the new request into the existing lightpaths, and (ii) setting up a new lightpath, for instance along the shortest-hop path from source to destination.

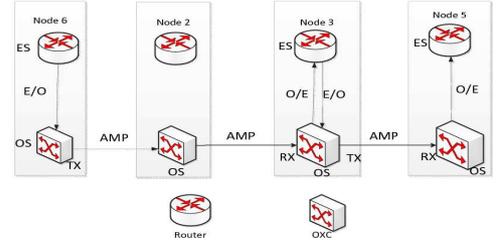


Fig. 2. Traffic flow in the grooming case

For traffic grooming, according to [7], the procedure is shown in Fig. 2. The traffic is electronically switched (ES) at node 6 and the signal is converted to an optical signal (EO). The signal is then optically switched (OS) and transmitted (TX). After being amplified (AMP) in the fiber, it is optically switched (OS) by node 2 and amplified to be received by node 3 (RX). As argued before, amplifiers' energy costs are fixed and hence not taken into account. After OS, the signal is converted to an electronic signal (OE), and multiplexed to the next connection by electronic switching (ES). There the signal is converted again to an optical signal (EO), and transmitted (TX) to node 5. Node 5 follows the same receiving procedure. Summing all these energy consumptions of grooming this traffic to lightpath 1 and lightpath 2 will lead to:

$$E_{groom} = (E_{es} + E_{eo} + E_{os} + E_{tx}) + E_{os} + (E_{rx} + E_{os} + E_{oe} + E_{es} + E_{eo} + E_{os} + E_{tx}) + (E_{rx} + E_{os} + E_{oe} + E_{es}) \quad (4)$$

Transponders are responsible for either O/E/O conversions or transmitting/receiving signals and their energy consumption

is denoted by $E_{tr} = E_{eo} + E_{tx} = E_{rx} + E_{oe}$. Considering that traffic grooming makes use of existing lightpaths, the energy consumption (overhead) of optical switching and transponders is already paid for by the existing lightpath (at least for the time it still remains, after which the cost corresponds to that of setting up a new lightpath for the remaining time), which leads to

$$E_{groom} = 3E_{es} \quad (5)$$

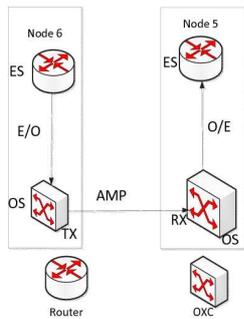


Fig. 3. Traffic flow in the new lightpath

The case for directly setting up a new lightpath is shown in Fig. 3 and can be expressed as:

$$E_{new} = 2(E_{es} + E_{tr} + E_{os}) \quad (6)$$

For traffic grooming, the IP layer electronic processing will be equal to

$$E_{es} = P_t * T * h \quad (7)$$

where h represents the request's holding time. Eq. 7 indicates that electronic processing is always traffic dependent and has no energy savings compared to setting up a new lightpath. After the end of the previously allocated lightpaths, the energy costs of traffic grooming equal those of setting up a new lightpath (for the remaining time h'), where $E_{es} = P_t * T * h'$ and E_{os} and E_{tr} behave as $P_0 * h'$. Note that both for traffic grooming and new lightpath,

Let us look at some cases in which traffic grooming is not the best solution. In our example $E_{groom} - E_{new} = E_{es} - 2(E_{tr} + E_{os}) = E_{es} - 72$. Unlike E_{tr} and E_{os} , E_{es} depends on the requested bandwidth b . Hence, if $E_{es} = 14.5b > 72$, i.e. $b > \frac{72}{14.5}$ Gb/s, then it is more energy efficient to set up a new lightpath than to do grooming. Another example would be where a request would need to be groomed onto many lightpaths, in which case the amount of electronic switching could become too costly. Finally, in some cases it may not be possible to groom traffic all the way from source to destination, which in some cases may render a new lightpath a more efficient solution.

IV. ENERGY-AWARE AUXILIARY GRAPH

In this section we propose an energy-aware algorithm for dynamic scheduled traffic. First, we introduce an auxiliary graph to represent the original topology and then each link in the auxiliary graph will be assigned energy weights, as specified in Section III. Finally, we apply Dijkstra's shortest path algorithm on each layer of the auxiliary graph to find the minimum energy consumption path to route the request. We present three types of auxiliary graphs, namely for when the network can offer (1) no wavelength conversion, (2) selective wavelength conversion, and (3) full wavelength conversion.

A. Auxiliary Graph without Wavelength Conversion

We use w to denote the number of wavelengths that each fiber link contains. We first assume that there is no wavelength conversion, such that the network can be regarded as w separate sub-layered graphs, one for each wavelength. Later, we also include wavelength conversion. Each network node is split into a physical IP node and an optical WDM node. These two types of nodes are connected via three types of links:

- Physical node: the IP source and destination nodes of a traffic request.
- Optical node: source and destination for a new established lightpath in the optical layer.
- Conversion link (*conv_link*): connects the physical and optical nodes, i.e. O/E (*conv_link_rx*) or E/O (*conv_link_tx*) conversion.
- Lightpath link (*light_link*): connects two physical nodes if they are the start and end of an existing lightpath.
- Optical link (*opt_link*): connects two optical nodes and could be used to establish a new lightpath.

For example, in the 3-node network of Fig. 4(a) with two existing lightpaths (using the same wavelength w_x), the corresponding auxiliary graph on the w_x layer will be represented as in Fig. 4(b).

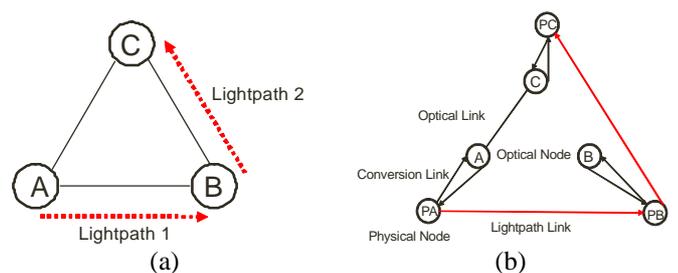


Fig. 4. (a) Original graph (b) Corresponding auxiliary graph

In this way w auxiliary graphs will be created to represent each wavelength of the original graph.

B. Weights Allocation

We will discuss how to allocate weights to the 3 different types of links.

1) **Optical and Conversion Links:** This case corresponds to the weight allocation when setting up a new lightpath. Note that the link between a physical node and an optical node represents the energy consumption at the IP layer. Hence, the energy consumption of the conversion link can be calculated as

$$E_{conv_link_rx} = E_{tr} + E_{os} \quad (8)$$

$$E_{conv_link_tx} = E_{es} + E_{tr} \quad (9)$$

where E_{tr} and E_{es} represent the energy consumption in the case of setting up a new lightpath. The conversion link which originates at an optical node will be allocated according to Eq. 8, while the conversion link originating at a physical node will be allocated according to Eq. 9. The conversion link originating at the optical node does not contain E_{es} when its corresponding physical node is not the destination node, because this is included in $E_{conv_link_tx}$ when the traffic leaves the physical node. Since traffic does not leave the destination node, it should be added there (as indicated in Sec. III). However, from an algorithmic perspective, the E_{es} contributions at the destination nodes are the same for traffic grooming and setting up a new lightpath, and they therefore do not affect the solution. To make the equations simpler, they have therefore been disregarded in the auxiliary graph. The same applies to the lightpath link weight. The weights of the optical link will represent the energy of optical switching, namely E_{os} .

2) **Lightpath Link:** The energy weight per time unit for a lightpath link will be set according to two cases, depending on whether the request's ending time is earlier than that (end) of an existing lightpath. We use E_{gnew} to represent setting up a new lightpath for the remaining time.

$$E_{light_link} = \begin{cases} E_{es} & t + h \leq end \\ E_{es} + E_{gnew} & t + h > end \end{cases} \quad (10)$$

where

$$E_{gnew} = 2E_{tr} + E_{es} + nE_{os} \text{ during time } (t + h, end) \quad (11)$$

and n denotes the number of nodes (including source and destination) that a lightpath traverses.

C. Auxiliary Graph with Wavelength Conversion

Although wavelength conversion consumes additional energy, it may reduce the blocking probability. Wavelength conversion can be easily incorporated into our auxiliary graph by connecting the w independent sub-layers. To do so, we make use of an extra virtual layer on which the path search will start and connect all layers to that virtual layer. Besides using the virtual layer as a starting point, it has the additional advantage that the existing lightpaths with weight E_{light_link} that were previously (in Section IV-A) present at each sub-layer need now only be present at the virtual layer, which reduces the total number of lightpath links. The physical nodes

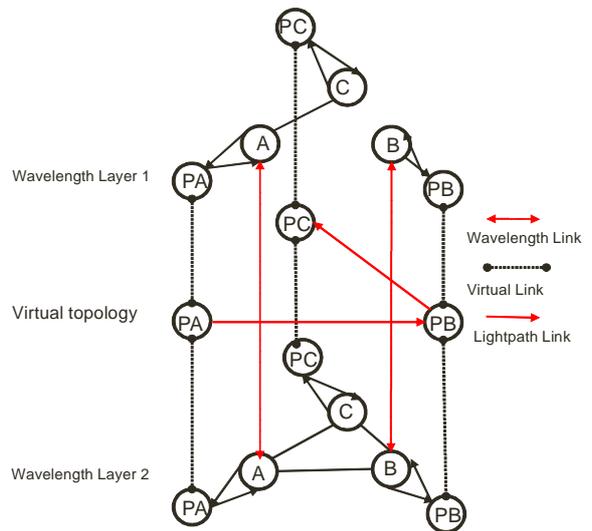


Fig. 5. Auxiliary graph for wavelength conversion

are connecting to their physical counterpart in the virtual layer by a virtual link ($virt_link$) of cost $E_{virt_link} = 0$. If, at some optical node, one can convert from that wavelength to another, then we add a wavelength link ($wave_link$) between those two optical nodes at the two corresponding sub-layers. The cost of that link equals the energy cost of wavelength conversion, which in our case is set to $E_{wave_link} = E_{tr}$ since wavelength conversion relies on an O/E/O operation. For example, in Fig. 4(a) there are already two existing lightpaths present in the network. To obtain the auxiliary graph, we first follow the procedure described in Section IV-A, thereby excluding the lightpath links. Subsequently we add the virtual layer, place the existing lightpath links, connect the physical nodes with their corresponding physical node in the virtual layer, and also add the wavelength links to obtain Fig. 5. In the example, nodes A and B are assumed to be able to convert to the other wavelength, and hence a link is drawn between the respective optical nodes.

The above-described way of connecting the wavelength conversion links is most versatile, since it can also capture the cases where wavelength conversion is only possible from a wavelength to a restricted range of other wavelengths (e.g., see [4]). If this restriction is not there and a node with wavelength conversion capabilities can convert to any other wavelength, we can use the virtual layer to reduce the number of wavelength conversion links. This time we would need to also represent the optical nodes in the virtual layer. If a node (say A) has wavelength conversion ability, then for all sub-layers a link connecting node A to its virtual companion is added. Instead of $\frac{w(w-1)}{2}$ links per node with wavelength conversion capabilities, w links now suffice (each with half the energy cost of wavelength conversion).

D. Algorithm and Complexity

For each new request we should update the auxiliary graph to reflect the proper weights and available capacity. If there is no wavelength conversion, after allocating weights to the links on each sub-layer of the auxiliary graph, running Dijkstra's shortest path algorithm on each sub-layer will allow us to choose the most energy-efficient route. In this case, the complexity of the algorithm per request is dominated by running Dijkstra's algorithm w times, which leads to an overall complexity of $O(wN \log(N) + wN^2)$ where N denotes the number of nodes in the original topology, and w represents the number of wavelengths in a fiber. N^2 instead of E (the number of links in the original topology) is used, because in the worst case $N(N-1)$ lightpaths (reflected in links) could be present.

In the general case with wavelength conversion, Dijkstra's algorithm is ran only once - starting from the source node at the virtual layer - but now on a larger graph. This leads to a complexity of $O(wN \log(wN) + wE + N^2 + w^2)$ for each request, where the term w^2 could be dropped if wavelength conversion goes through the virtual layer.

V. SIMULATIONS

We compare our energy-aware routing algorithm, in terms of energy consumption and blocking, to the method of directly setting up new lightpaths (Direct New Lightpath) based on the shortest path and to a traffic grooming algorithm. The traffic grooming algorithm tries to select paths on which the request can be completely groomed. If multiple such paths exist, the one using the least amount of lightpaths is chosen. If no such path exists, then a new (shortest hopcount) lightpath will be set up. If this option also fails, we select a path that partly grooms and partly uses a new lightpath. Else, the request is blocked. We simulate these three algorithms under two cases: one where wavelength conversion is permitted and each node has full wavelength conversion abilities (represented by WC), and the other one where wavelength conversion is not permitted (represented by NWC). We simulate on two realistic carrier backbone networks, namely the NSFNet of 14 nodes and 20 links and the USANet of 24 nodes and 43 links (see Fig. 6).

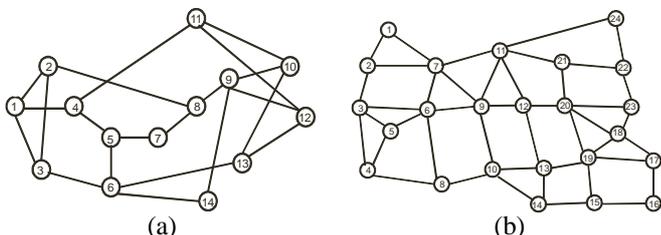


Fig. 6. (a) NSFNet and (b) USANet

We vary the amount of traffic requests from 1000 to 10000, where s and d are randomly generated and the holding time h also randomly varies. The requested capacity b will be generated according to the distribution $OC-1, OC-3, OC-$

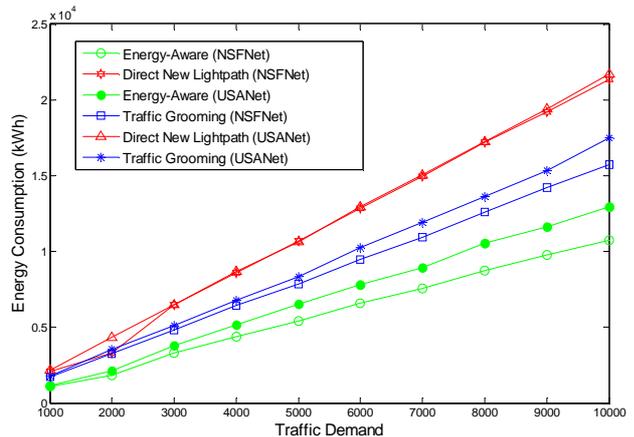


Fig. 7. Energy consumption in two networks

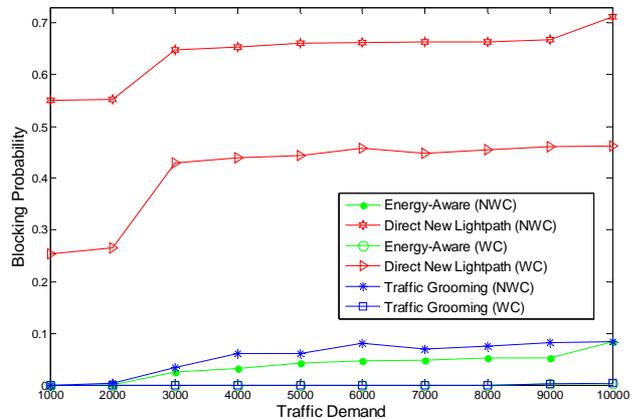


Fig. 8. Blocking probability in the NSFNet

12, $OC-48$ and $OC-192$ as $20 : 10 : 10 : 4 : 1$. The number of wavelengths per link is chosen as 40 and 200.

Fig. 7 gives the energy consumption of the three algorithms in the NSFNet and the USANet. We set the number of wavelengths to 200, so that no blocking happens. From this figure we can see that the energy consumption grows almost linearly with the amount of traffic, but the slope is smallest for energy-aware routing. To not clutter the figure, we omitted the results for wavelength conversion, since, with ample wavelengths, wavelength conversion was not needed and thus never used (giving the same results as for without wavelength conversion).

Figs. 8 and 9 show the blocking probability in the two networks when the number of wavelengths is set to 40. Due to the use of traffic grooming, energy-aware routing obtains a lower blocking probability than shortest path routing. However, there is even a slight improvement over the traffic grooming algorithm. This is because in some cases the traffic grooming algorithm tries to groom over many lightpaths, while the energy-aware algorithm would opt for a short new light-

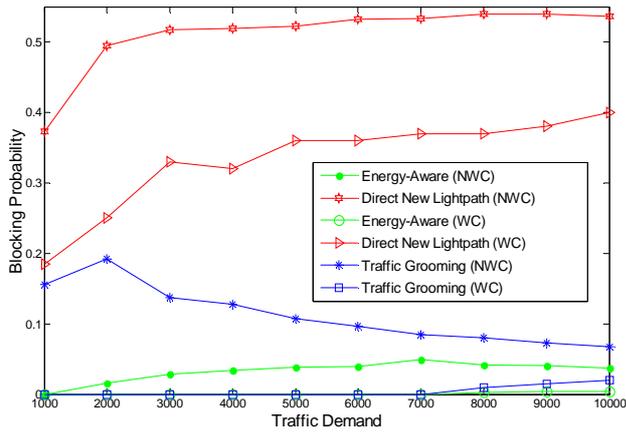


Fig. 9. Blocking probability in the USANet

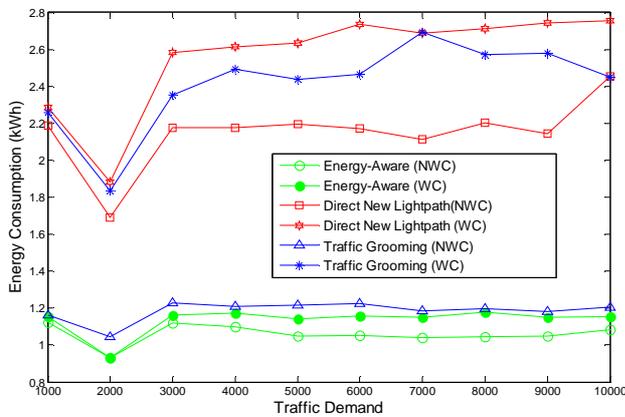


Fig. 10. Average energy consumption per accepted request in the NSFNet when links have 40 wavelengths

path. Clearly, the use of wavelength conversion reduces the blocking probability even further. Due to the different blocking probabilities, comparing based on total energy consumption would give a wrong reflection. Hence, in Figs. 10 and 11, we present the average energy consumption per accepted request. Reflected in such a metric, it is possible to see the extra energy cost in wavelength conversion. We believe that in practice, these extra energy costs pale in comparison to the extra revenues gained by being able to allocate more requests.

VI. CONCLUSIONS

We have proposed an energy-aware routing algorithm for dynamic scheduled traffic. By applying an energy model to compute the energy consumption at the IP and optical layer, the algorithm can attain practical energy consumption weights. Our model also allows to take the energy costs of full or sparse wavelength conversion into account. Simulation results show that the proposed algorithm can achieve a lower energy

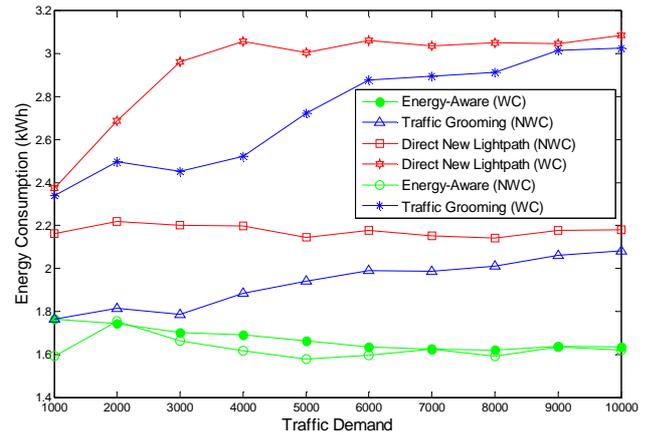


Fig. 11. Average energy consumption per accepted request in the NSFNet when links have 40 wavelengths

consumption and blocking probability compared to directly setting up new lightpaths or traffic grooming in an energy-oblivious way. Because wavelength conversion costs energy, it is only used when it is really need to prevent blocking a request and otherwise it prefers wavelength continuous routes.

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