Power Reduction in WDM Mesh Networks Using Grooming Strategies

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Abstract. This work reports on the benefits of using energy-efficient grooming strategies in WDM mesh networks in terms of the overall network power consumption. We examine a key enabling node architecture called tap-or-pass (TOP) and demonstrate how it can support lightpath *extension* and lightpath *dropping*. Using these grooming concepts we propose several grooming strategies. Through extensive simulation, we demonstrate that, given a network with dynamic traffic requests, the proposed grooming strategies lead to considerable energy saving and comparable request blocking, in particular when the network load is moderate.

Keywords: Green Networking, Energy Efficiency, Optical Networks, Routing and Traffic Grooming.

1 Introduction

As the Information and Communication Technology (ICT) infrastructure grows more electrical power will be required to support telecommunication networks. In fact, it is estimated that in the developed countries approximately five percent of the total electrical energy is consumed by the telecommunication and IT industry [1]. In the developing nations, ICT infrastructure consumes approximately one percent of the total electricity consumption [2] and as higher-speed national broadband access networks grow, this number is expected to increase exponentially. Consequently, a large body of works have concentrated on studying and reducing energy consumption in critical areas such as chip design [3, 4], wired-line networks [5,6], and servers and application [7]. However, only limited attention has been devoted to study energy efficient optical networks. In fact, while optical networks continue to be the champion of future networks (e.g., 400 GigE and 1 TbE [8]) due to their high capacity, low transmission loss, transparency to signal rate and format, and resilience to noise and environmental harsh conditions, their power consumption is substantially high and manifests considerable operational cost.

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In recent years, a number of studies, such as [9, 10] and [11], have focused on comparing the the power consumption of photonic and electrical subsystems in an optical cross-connect in WDM networks. In their survey, the authors of [12] provide a detailed overview of energy conservation approaches across core, metro, and access levels of optical networks.

In study of energy-efficient optical networks, a number of efforts have been dedicated to develop energy-aware grooming mechanisms, including [13–16]. One potential issue with the above traffic grooming proposals is that they require activating power-hungry electronic multiplexers and demultiplexers in the electronic layer of optical cross-connects. Thus, in order to support traffic grooming, the dropped optical traffic, or *lightpath*, has to be converted into electrical form using optical-electrical (OE) converters. Furthermore, the remaining traffic must be converted back to optical form using electrical-optical (EO) converters prior to retransmission of the lightpath toward downstream nodes. Such signal conversion and switching is known to be power intensive [17].

In this work we focus on energy-aware traffic grooming in WDM networks where lightpaths are shared between multiple requests, and local traffic is only dropped optically. Thus, the dropped traffic at intermediate nodes no longer has to go through electronic devices in order to be added and retransmitted. The key enabling technology to support optical dropping at intermediate nodes, while passing the lightpath to other nodes, is the tap-or-pass (TOP) node architecture. In this architecture, the incoming lightpaths can pass through intermediate nodes *or* have their power split unequally so that a small portion of the optical energy is dropped while the rest of the energy is passed to the subsequent downstream nodes. Similar node architectures have been discussed for various applications in previous literature, including [18].

Motivated by our earlier work in [19], [20], and [21], we demonstrate the benefits of exploiting the TOP architecture to support energy-aware traffic grooming in optical networks. Using TOP-enabled nodes, we evaluate the energy saving benefits of two grooming concepts called *lightpath dropping* and *lightpath extension*. We refer to these as *lightpath-based grooming* (LBG). In the lightpath dropping approach, a lightpath can pass through an intermediate node, while partially being dropped. Lightpath extension on the other hand, is based on optically extending an existing lightpath beyond its original terminating node. The key contribution of this work compared to [20] is that we present the details of the auxiliary graph and how the LBG algorithms are implemented when traffic requests arrive dynamically.

Through simulations, we evaluate the performance of lightpath dropping and extension using our proposed grooming algorithms in terms of energy usage and request blocking probability. We compare our results with traditional grooming techniques as described in [22].

The rest of this paper is organized as follows. In Section 2, we describe details of the TOP node architecture. In Section 3, we model the TOP-enabled network and mathematically compare lightpath dropping and lightpath extension in terms of power budget. In Section 4, we describe the grooming algorithms and our proposed auxiliary graph. Then, in Section 5, we provide our simulation results. In Section 6, we conclude the paper.

2 Network Architecture and Problem Formulation

In general, a WDM node with grooming capability has a two-layer architecture composed of an optical cross-connect (OXC) and an electronic switch. The OXC may be accompanied with wavelength converters, in which the incoming wavelengths can change color prior to leaving the switch.

A typical electronic switch layer in a WDM node with grooming capacity consists of electronic-optical-electronic (EOE) and optical-electronic-optical (OEO) converters, multiplexers and demultiplexers, and a grooming switch fabric. Each multiplexer, in turn, may have one or more transmitters and receivers, each connected to an add or drop port on the OXC, respectively. Add/drop ports, shown in Fig. 1(a), allow the lower rate signals to be inserted (or extracted) into the high-speed optical signals.

2.1 TOP Architecture

In this paper we use a modified OXC, as shown in Fig. 1(b). In this architecture an incoming lightpath can pass through the OXC (maintaining its full power) *or* tap-or-pass using a passive unbalanced splitter. Using the tap-or-pass (TOP) architecture, only a small portion of the incoming optical optical power is dropped and the rest can be sent to the next node. When a lightpath is terminated at a node, it is simply tapped and the rest of the energy can be ignored. As noted before, when wavelength conversion capability is available, the continuing portion of the optical signal can be carried using a different color.

One drawback of the TOP architecture is that it reduces link utilization by carrying extra traffic. This is because the aggregated traffic will be reaching all the nodes visited by the lightpath. Another issue with the TOP architecture is that as lightpaths are tapped their optical power is reduced, and thus, they will have shorter reach. The main motivation in implementing the TOP architecture, however, is that it reduces the overall energy consumption of the node because it no longer requires turning on the electronic multiplexers (including transmitters and OEOs) of a node in order to *retransmit* the remaining dropped traffic.

The TOP architecture offers two distinct features: *lightpath dropping*, which refers to the ability to drop a lightpath on the intermediate nodes, and *lightpath extension*, which refers to extending a lightpath beyond its current terminating node to a new node. These features are depicted in Fig. 2. A typical point-to-point lightpath between a source-destination node pair is shown in Fig. 2(a), where the lightpath is terminated at Node 1. Fig. 2(b) shows how the same lightpath can be dropped at intermediate Node 0. Lightpath extension to Node 2, beyond the original terminating node (Node 1) is demonstrated in Fig. 2(c). A combination of lightpath dropping and lightpath extension is shown in Fig. 2(d). An important feature of the TOP architecture is that no traffic interruption

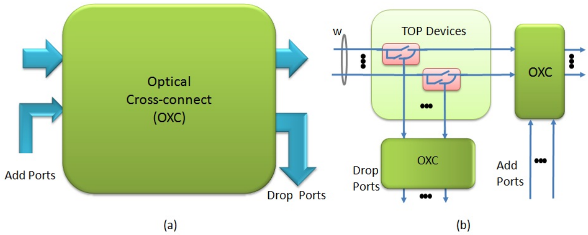

Fig. 1. Optical crossconnect of a WDM node with (a) add/drop ports and (b) with tap-or-pass (TOP) capability

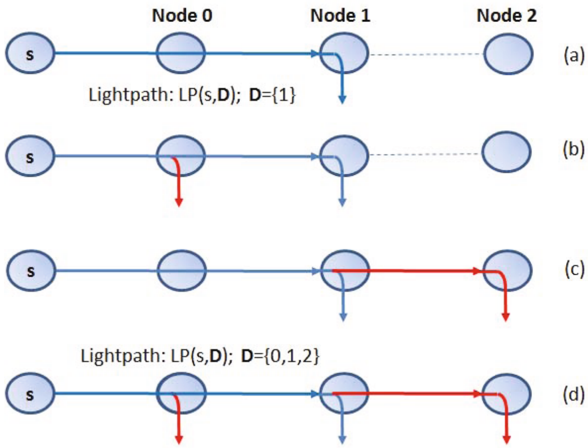

Fig. 2. A network with (a) point-to-point lightpath connections; (b) lightpath dropping at an intermediate node; (c) lightpath extension; and (d) combination of lightpath dropping and extension

occurs as a lightpath is dropped or extended to other nodes, as long as all nodes are receiving appropriate amount of optical power.

2.2 Problem Formulation

The energy-efficient traffic grooming problem formulation can be stated as follows. Given the network topology with all nodes being TOP-enabled, the number of wavelengths per link, the number of transceivers at each node, and the incoming traffic request, find the routing and wavelength assignment for the requested traffic demand on the virtual topology such that minimum power consumption is achieved in the network. In the following sections we demonstrate how lightpath-based grooming (LBG) can be utilized to improve the overall energy saving of the network without degrading its performance.

3 Power Budget Model

A critical aspect of implementing lightpath-based grooming is ensuring a minimum power level at all nodes. Thus, as a lightpath is extended or dropped at other nodes, the power budget must be recalculated to ensure that all nodes receive a sufficient amount of optical power. In this section, we provide a power budget model for LBG. Using this model it is possible to evaluate the feasibility of LBG.

We assume that a lightpath between a source-destination node pair (s, d), denoted by $LP(s, d)$, can be dropped at any node k, including an intermediate node, the destination node d, or an extended node one or more hops away from node d. Therefore, $LP(s, D)$, can be modeled as shown in Fig. 3, starting at node s and passing through a set of nodes, $D = [0, 1, 2, ..., k]$. We define P_k as the amount of power available towards the downstream node and $P_k \cdot G_k^{-1} \cdot (\frac{\alpha}{1-\alpha})$ as the amount of power received by any intermediate or ending node k along a given lightpath. In this expression, α is the portion of power dropped at each node's receiver $(0 < \alpha < 1)$, and G_k is the optical power amplification performed by node k prior to passing the lightpath to the next node. In general, the power budget model using TOP-enabled switches can be expressed as

$$P_k = [(P_{k-1} - L_k) \cdot (1 - \alpha.s_k)] \times G_k \ \forall k \in D, k \neq s. \tag{1}$$

In the above formulation, L_k is the power lost in the link connecting two consecutive nodes $k-1$ and k, due to attenuation. We define matrix $S = [s_0, s_1, ..., s_k]$ as an indicator in which $s_k = 1$ represents the drop of lightpath at node k and $s_k = 0$ indicates that the lightpath is passing through node k and no splitting is performed. For example, in Fig. 2(c), $S = [0, 1, 1]$ indicates that the lightpath is being dropped at Node 1 and Node 2. In our analysis, we assume that all nodes have the same gain, G, and link loss, L. We denote the initial output optical power of a lightpath at a source node by P_s.

The amount of power *dropped* at each node k must be at least P_{min}, depending on the sensitivity of the node's receiver:

$$\frac{P_k}{G_k} \cdot (\frac{\alpha}{1-\alpha}) \geq P_{min}. \tag{2}$$

Therefore, as a lightpath is dropped on an intermediate node, the power received by the last node on the lightpath does not fall below P_{min}. On the other hand, an existing lightpath can only be *extended* by h hops from node d to $\grave{d} = d + h$, without any type of amplification, $G = 1$, if

$$\frac{P_{\grave{d}}}{G_{\grave{d}}} . (\frac{\alpha}{1-\alpha}) = P_d \cdot (h \cdot L) \geq P_{min}. \tag{3}$$

For example, in Fig. 2(c) $h = 1$ and $P_{\grave{d}}$ refers to the available power at Node 2.

Referring to Eqn. 1, it is possible to rearrange the expression as follows:

$$P_k = [(1 - \beta_k) \cdot (1 - \alpha.s_k)] \times G_k \times P_{K-1} \ \forall k \in D, k \neq s, \tag{4}$$

where we define $\beta_k = L_k/P_{k-1}$ as the *link loss ratio*. Clearly, $0 < \beta_k < 1$. A closer look at the above expression suggests that, for a given lightpath between two or more nodes, when the dropped portion of power at each node is much larger compared to the link loss ratio, $\beta_k >> \alpha$, lightpath dropping is more power efficient compared to lightpath extension. That is, for an existing lightpath $LP(s, d)$, lightpath dropping results in larger available power at the terminating node d to be forwarded downstream.

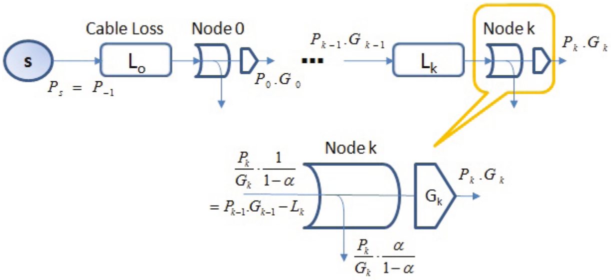

Fig. 3. Power budget model for supporting lightpath extension and lightpath dropping using TOP-enabled node architecture

In our analysis, we assume that the output power is such that $P_s \geq (h_{max} \cdot L) \cdot \alpha$, where h_{max} is maximum hop distance of the network. In other words, all lightpath has sufficient power to be terminated at any node in the network.

4 Lightpath-Based Grooming (LBG)

In this section we discuss the implementation of a lightpath-based grooming, including lightpath dropping and lightpath extension. The principle of the LBG is similar to the auxiliary graph described in [19]. However, the key difference is that we combine the graph model with the power budget model, described in Section 3.

4.1 Auxiliary Graph Model

Given a network with N nodes and W wavelengths per fiber link, the physical network can be represented by a graph $G_p = (V_p, E_p)$. In this representation, V_p is the set of network nodes, and E_p is the set of links connecting the nodes. The current status of the network can be modeled by a W-layer auxiliary grooming graph, $GG = (V, E)$, where each layer corresponds to the state of a wavelength in the network. A vertex $v \in V$ in the auxiliary graph, GG, represents the optical receiving or transmitting capabilities of a physical node on a particular wavelength layer. Therefore, a physical node can be represented by W receiving and W transmitting vertices.

On the other hand, E is a set of weighted directional edges which corresponds to available optical paths between node pairs. In our graph model, we define two basic edge types, namely, *grooming* edges and *optical* edges. A grooming edge abstracts the node's grooming capacity enabling an optical signal to be dropped and processed electronically. Therefore, for each physical node, there will be one grooming edge between a single receiving vertex and each transmitting vertex. We denote a grooming edge from a receiving vertex on layer x to a transmitting vertex on layer y on node i by $GP_i^{x,y}$.

An optical edge, on the other hand, represents an all-optical path between a node pair. Depending on the node architecture, in our graph model, we define the following optical edges, which can be established between a node pair (i, k) with one intermediate node j or more, on wavelength layer w:

– *Existing lightpath*, LP_{ik}^{w}, describing an active lightpath currently carrying traffic between nodes i and k;
– *Potential lightpath*, PLP_{ik}^{w}, representing one or more available wavelength links, which can support a new lightpath from node i to k;
– *Potential extended lightpath*, $PELP_{ik}^{w}$, expressing an existing lightpath, LP_{ij}^{w}, which can potentially traverse optically beyond its current end node, j, and reach node k through one or more available wavelength links;
– *Sub-lightpath*, SLP_{ij}^{w}, describing a possible optical connection between the source node, i, and an intermediate node, j, of the existing lightpath, LP_{ik}^{w}.

Note that for each existing lightpath with I intermediate nodes, there will be as many as I sub-lightpaths, all having the same free capacity. These concepts are illustrated in Fig. 4(a).

The lightpath-based grooming algorithm with intermediate dropping and extension capacity (LPwDwE) supports two basic operations in order to route new connection requests: (1) existing lightpaths can be dropped at their intermediate nodes, while continuing their path to the end node; (2) existing lightpaths can be extended beyond their end nodes. These concepts are shown in Fig. 4(b). The main motivation for implementing the LPwDwE is to provide higher flexibility in finding the most appropriate routing path between a node pair.

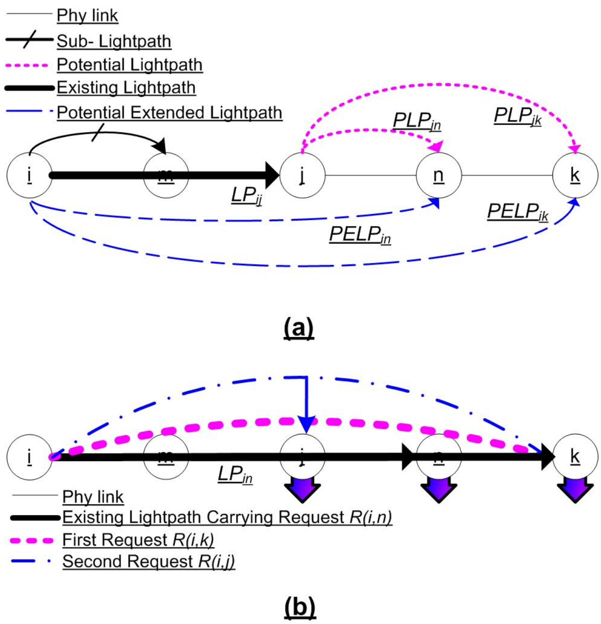

Fig. 4. (a) Illustration of different optical edges used in the auxiliary graph; (b) The LPwDwE algorithm allows lightpath extension to node k and dropping on intermediate nodes j and n

The LPwDwE algorithm consists of two basic routines: *ReqSetup* and *ReqTeardown*. For each new connection request, the *ReqSetup* routine constructs a new auxiliary graph representing the current status of the network and finds the shortest path between the requested node pair. Details of the *ReqSetup* routine upon arrival of a new request $Req(s, d, B)$, where s and d are the source and destination nodes, respectively, and B is the request's demand, are described in Table 1.

Table 1. Algorithm description for the *ReqSetup* routine in LPwDwE

For a given request $Req(s, d, B)$:

1. For each wavelength layer w and each node i on the physical graph G_p
   (a) Find the shortest path between node i and every other node j, such that a potentially new lightpath can be established between the two nodes, PLP_{ij}.
   (b) For every existing lightpath, between nodes i and j, LP_{ij}, with free capacity $C_f \geq B$,
      i. Find all possible sub-lightpaths between node i and all the intermediate nodes on LP_{ij}.
      ii. Find all possible potential lightpaths by extending LP_{ij} on available links.
   (c) Assign weight to all edges including potential lightpaths, potential extended lightpaths, existing lightpaths, sub-lightpaths, and grooming edges according to the grooming policy.
2. Search for the shortest path on the auxiliary graph between node s and d. If no such path was found, discard the request; otherwise, continue to next step.
3. Set up the route for the request $Req(s, d, B)$ and update the network status to reflect the latest connections and available resources.

On the other hand, when a request is completed the *ReqTeardown* routine is executed and operates as follow:

– *Step 1*: The request's demand is removed from all lightpaths carrying the request;
– *Step 2*: All *inactive* wavelength links along lightpaths carrying the request are removed. If all wavelength links on a lightpath are inactive, the entire lightpath will be removed;
– *Step 3*: The network state is updated accordingly to represent the latest available resources.

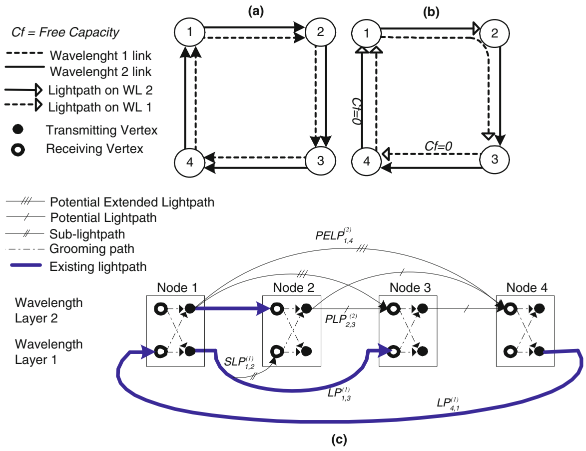

Fig. 5. (a) An example of a four-node network with two wavelengths in each fiber; (b) the current state of the network with available wavelength links; (c) the auxiliary graph, GG, for the current state of the network shown in (b).

4.2 Example

We illustrate the above concepts by means of an example. Fig. 5(a) shows a four-node network with four unidirectional fiber-links, each having two wavelengths. Each node is equipped with two transmitters and two receivers and has full-grooming capacity (the entire incoming data can be groomed). Initially, we assume that no connections exist in the network. Fig. 5(b) shows the current state of the network after a number of connection requests are established. Upon arrival of a new request, the auxiliary graph, shown in Fig. 5(c) can be established. We assume $LP^1_{3,4}$ and $LP^2_{4,1}$ have no available bandwidth and thus they are not shown in the auxiliary graph. Using the two available wavelength links between node pairs (2,3) and (3,4), we can generate 3 distinct potential lightpaths on Layer 2. The existing lightpath between node pair (1,2) can also be extended to Nodes 3 and 4. Furthermore, the existing lightpath on wavelength Layer 1 between Nodes 1 and 3 can support a sub-lightpath between node pairs (1,2), denoted by $SLP^1_{1,2}$. Let us assume that Node 3 requests a new connection to Node 2. Based on available resources, indicated by the auxiliary graph in Fig. 5(c), this request can be satisfied through the following shortest multi-hop path: $PLP^2_{3,4}$, $GP^{2,1}_4$, $LP^1_{4,1}$, $GP^{1,2}_1$, and $LP^2_{1,2}$.

4.3 Algorithm Complexity

The complexity of LPwDwE is mainly attributed to the *ReqSetup* routine, which in turn is directly tied to complexity of the shortest path algorithm. For example, assuming we implement Dijkstra's shortest path algorithm, the worst-case complexity of the *ReqSetup* will be equivalent to finding all available shortest paths between all nodes on all wavelength layers *and* the shortest path for the $Req(s, d, B)$ among all layers between the node pair (s, d). Thus, the worst-case complexity will be equivalent to $O(wn^3) + O((nw)^2)$. Note that if the number of wavelengths is much larger than the number of nodes in the network, as is the case in backbone networks with dense WDM links, the dominating factor will be $O((nw)^2)$.

4.4 Grooming Strategies

In our study, we consider several grooming strategies. Below we briefly describe each one.

- Minimize the number of logical hops (MinLH), i.e., minimize electronic processing for connection requests. In this case, the total cost to establish a connection will be based on the number of logical hops.
- Minimize the number of physical hops (MinPH), i.e., maximize the wavelength utilization. Thus, the total end-to-end cost will be equivalent to the number of physical hops between the source-destination node pair.
- Minimize the number of new lightpaths (MinNL), i.e., minimize the number of transmitters and receivers.
- Minimize the number of physical hops on lightpaths carrying the request (MinTH), i.e., maximize the wavelength utilization. In this case, the weight assignment for all optical links is equivalent to the number of physical hops on the entire edge, including the ones beyond the destination node.

Using the auxiliary graph, when several shortest paths are available for a single connection request, a secondary objective is chosen to select the most appropriate available route. For example, assuming that the main objective is to minimize the number of logical hops, and more than one such route is available, the route with the least number of logical hops is selected.

When limited resources are available, the above LBG strategies lead to a different utilization of the network resources and, thus, to a different level of network performance, in terms of request blocking probability and energy consumption.

5 Performance Analysis

In this section, we describe simulation results obtained by implementing the aforementioned algorithms in the TOP architecture. The schemes are evaluated in terms of blocking and energy consumption. In our simulation, we consider the 14-node NSF network with 21 bidirectional links. We assume each link supports 4 wavelengths in each direction, operating at OC-192 rate. Connection requests are generated dynamically, following a Poisson process with uniform distribution among the node pairs. The connection requests are uniformly distributed among OC-3, OC-12, or OC-48 rates. We assume that there is no wavelength conversion.

Unless otherwise mentioned, there are 4 transmitters and 4 receivers in each node. The power consumption of the grooming module (transmitter or receiver, including the E/O and O/E) is 160 W/module [23]. This figure is based on the power consumption figure of the Cisco Catalyst 6500 series published in [24]. For our analysis we assume that only 5% of the power is dropped at each node and that the remaining of power will pass through the TOP device. We assume that all unused modules (i.e., modules not processing traffic) are in idle mode and consume a negligible amount of power. In order to obtain the following results, we took the average of 105 experiments for each data point, presenting a 95% confidence interval.

5.1 Comparing Grooming Strategies

We first examine the performance of LBG strategies. Then, we compare the performance of lightpath extension and lightpath dropping for a given grooming strategy.

Fig. 6 displays the blocking probability obtained by implementing different grooming strategies, namely, MinLH, MinPH, MinNL, MinTH, as a function of the load, when the overall network load varies from 20% to 98% of the network capacity. In this case, we assume each node can perform *both* lightpath extension and lightpath dropping. This figure shows that, regardless of the grooming strategy, when the number of transmitters and receivers are limited, implementing TOP can improve the overall blocking probability when compared to traditional grooming (NoTP), particularly at lower loads. The reason that none of the grooming strategies performs better than NoTP at higher loads is due to the fact that lightpath dropping and lightpath extension carry the entire groomed traffic to all intermediate and extended nodes, thus lowering the network utilization.

Fig. 6 indicates that when the number of receivers and transmitters is limited, the best performance is achieved using the MinTH grooming policy. This figure also suggests that, among the proposed grooming policies, the poorest performance is achieved by MinNL. Note that, using MinNL, the LBG strategy attempts to use available resources before establishing new lightpaths.

Fig. 7 depicts the total energy usage in kilowatt-hour when LBG strategies are implemented, compared to the traditional grooming (NoTP). We note that, based on our results, all the proposed grooming strategies perform consistently better then NoTP in terms of energy efficiency.

Comparing Fig. 6 and Fig. 7, we observe that, in general, for moderate loads, NoTP experiences higher blocking and energy consumption. We also observe that MinNL strategy experiences a high blocking and high energy consumption compared to other grooming strategies. On the other hand, MinLH appears to perform the best in terms of both network performance and energy consumption.

Fig. 8 shows the percentage of annual energy savings in the network with the TOP architecture when compared to traditional grooming. In our calculation of energy savings, the power consumption for cooling (e.g., air conditioning the building) is not considered. Furthermore, it is assumed that the electronic switch fabric is always fully active, independent of the traffic load. We believe these two assumptions make the energy saving results very conservative. Our results indicate that energy savings of up to 20% can be achieved by exploiting TOP

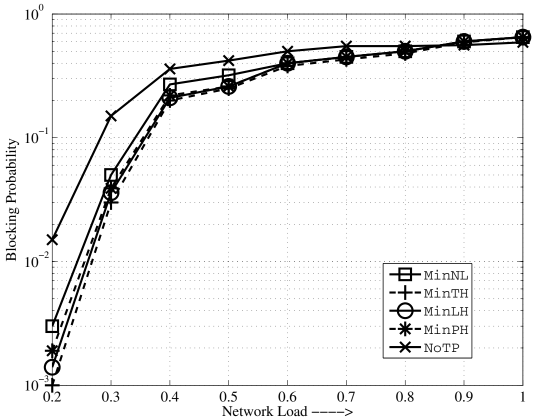

Fig. 6. Blocking probability comparison between different grooming strategies when both lightpath dropping and extension are allowed

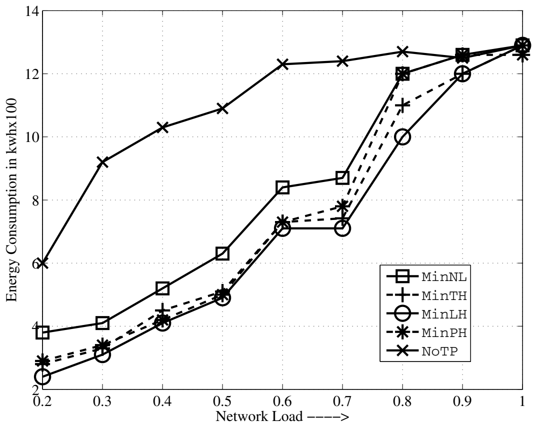

Fig. 7. Energy consumption comparison between different grooming strategies when both lightpath dropping and extension are allowed

architectures when the network load is low. As the network load increases, the impact of using TOP architecture is reduced and eventually all the electronic devices in nodes must be activated.

5.2 Comparing Lightpath Dropping and Extension

In this section we compare the performance of lightpath dropping and lightpath extension in terms of blocking and energy consumption. Fig. 9 compares the blocking probability using MinLH for the following cases: lightpath dropping only (WD-NE); lightpath extension only (ND-WE); and both lightpath extension and light dropping (WD-WE). Our results indicate that, in general, WD-WE consistently performs better over different load values, particularly when the load is low.

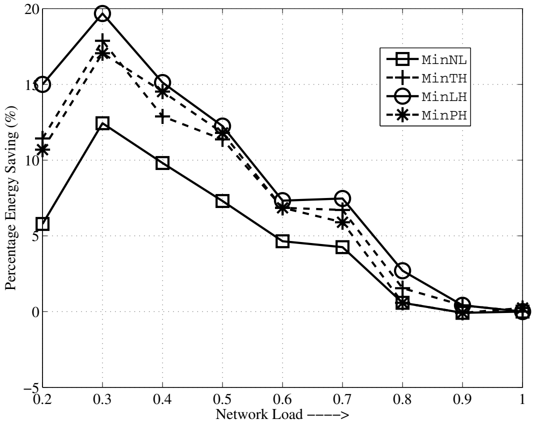

Fig. 8. Annual energy saving in dollars compared to NoTP

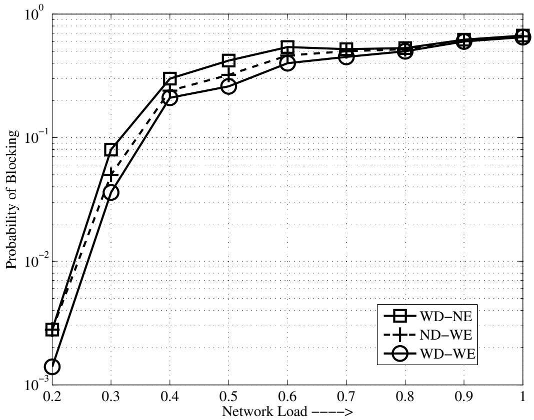

Fig. 9. Comparing blocking probability with MinLH using lightpath dropping only (WD-NE) lightpath extension only (ND-WE), and both lightpath extension and light dropping (WD-WE)

6 Conclusion

In this work we examined the energy saving benefits of tap-or-pass (TOP) node architecture in optical mesh networks. Using this architecture we reported on performance comparison between different lightpath-based grooming strategies. Our results demonstrate that in general, when the number of tributary transmitters and receivers is limited, lightpath-based grooming using the TOP paradigm can perform better in terms of blocking probability, particularly, when the network load is low. Furthermore, the proposed lightpath grooming policies can offer moderate energy savings and thus, operational expenditure reduction.

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