Energy Efficient Time-Aware Traffic Grooming in Wavelength Routing Networks

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***Abstract*—In this paper, we investigate both static and dynamic traffic grooming problems in a wavelength routing network, so as to minimize the total energy consumption of the core network, with the additional consideration of the holding times of the lightpaths and connection requests. In static case, all connection requests with their setup and tear-down times are known in advance, we formulate an Integer Linear Programming (ILP) to minimize the energy consumption. In dynamic case, we adopt a layered graph model called Grooming Graph and propose a new traffic grooming heuristics called Time-Aware Traffic Grooming (TATG) which takes the holding time of a new arrival connection request and the remaining holding time of existing lightpaths into consideration. We compare the energy efficiency of different traffic grooming policies under various traffic loads, and the results provide implications to choose the most energy-efficient traffic grooming policies under various scenarios.**

***Index Terms*—Energy efficient, traffic grooming, time awareness**

I. Introduction

The energy consumption of the backbone network is rapidly growing with the traffic and thus the concept of "Green Networking" has recently aroused much attention from the research community. Therefore it is highly desirable to minimize the energy consumption in network planning and resource optimization.

Traffic grooming problem in optical wavelength routing network has been extensively studied with the aims to minimize the number of optical-electronic-optical conversions (OEOs), or maximize the total number of users served in the optical networks. Thus, the network bandwidth utilization can be optimized. In [2], a mathematical formulation of traffic grooming and several heuristics were proposed in order to improve the network throughput. In [3], a novel generic graph model was proposed to achieve various traffic grooming policies by just modifying the weights of the edges in the graph model. Both [2] and [3] dealt with static traffic grooming problem in which all connection requests were known in advance. In [4], the novel generic graph model in [3] was applied to a dynamic traffic grooming problem in which connection requests arrived at the network randomly. In [5], a layered Grooming Graph was proposed to investigate the survivable traffic grooming algorithms. In [6], the holding time information of connections was exploited to improve the traffic grooming performance in terms of blocking probability. In [7], the traffic grooming problem was studied under a sliding scheduled traffic model in which the holding duration of connections could slide in a larger time window.

Since traffic grooming requires electrical multiplexing and OEO conversion which induce much energy consumption, recently, there is growing interest in achieving energy efficient traffic grooming. In [8], both MILP and heuristics were reported to solve the energy-minimized static traffic grooming problem for IP over WDM Networks. In [9], two different models of power consumption of optical networks were proposed: flow based formulation and interface based formulation. The work in [10] adopted the interface based formulation and formulated an Integer Linear Programming (ILP) for the traffic grooming problem with the objective of minimizing the power consumption. In [11] and [12], a more detailed energy consumption model considering the modular structure of optical network nodes was presented and a similar layered graph model to [3] was adopted to solve the dynamic traffic grooming problem.

As far as we know, existing works on energy-efficient traffic grooming do not consider a very important factor in energy saving – time, as energy consumption is the product of both power and time. Hence, minimizing the power consumption may not necessarily minimize the energy consumption. In this paper, we study both static and dynamic traffic grooming problems with an additional consideration of time information.

A. Energy consumption model

In this paper, we adopt the interface based formulation in [10] as the power consumption model. In this model, it is assumed that the main power consumption components in optical network are the ports of DXC (Digital Cross Connect) and OEO conversions. Compared to electronic domain, optical domain components consume much less power. So the power consumption of the whole network is calculated as the sum of the power consumption of individual lightpaths. The power consumption of a lightpath $P_{lightpath}$ is assumed to have a linear dependence with the amount of traffic and is represented as:

$$P_{lightpath} = P_0 + p \times b_l \tag{1}$$

where P_0 is the fixed power consumption once the components of a lightpath are turned on, even if the lightpath carries no traffic. p is the coefficient which denotes the power consumption per additional unit traffic. b_l denotes the amount of traffic carried on the lightpath. It is also assumed that the inactive components can be shut down when there is no traffic. As far as we know, there is still lack of accurate power consumption model for optical network components. Although our work adopts interface based formulation, for simplicity, our following formulation and algorithms are applicable to other power consumption models by just modifying the objective function in the static traffic grooming and modifying the Grooming Graph in the dynamic case.

The rest of the paper is organized as follows. In section II, the ILP formulation for the time-aware static traffic grooming is introduced. In Section III, new time-aware traffic grooming heuristics *TATG* is proposed for dynamic scenario. In Section IV, simulation results are presented to compare the performance of different traffic grooming policies. Section V concludes the paper.

II. STATIC TRAFFIC GROOMING WITH TIME AWARENESS

A. Scheduled Traffic Model

In static traffic grooming with holding time awareness, all connection requests with their setup and tear-down times are known in advance. This is similar to the Scheduled Traffic Model in [13]. Each connection request is represented by $r(s, d, b, t_s, t_e)$, where s and d denote the source and destination node, respectively; b denotes the bandwidth requested, which is the amount of traffic in units of the minimal granularity (e.g., OC-1); t_s and t_e are the requested setup and tear-down times, respectively.

B. ILP Formulation

The network topology $\boldsymbol{G = (V, E)}$ is given as an undirected graph. $\boldsymbol{V}$ is the set of network nodes capable of traffic grooming. $\boldsymbol{E}$ is the set of undirected fiber links. It is assumed that each fiber can support W wavelengths and the capacity of each wavelength is in multiples of the minimal granularity (e.g., OC-1), represented by C. The set of all connection requests is denoted by $\boldsymbol{R}$. The connection requests and the established lightpaths are both bidirectional. b_r denotes the bandwidth requested by connection request r. In static traffic grooming, we assume that the network capacity of the network is sufficient to accommodate all connection requests. The objective of our ILP formulation is to minimize the total energy consumption of establishing all the connection requests.

In the formulation, the setup and tear-down times of all connection requests divide the continuous time period into time slots, whose duration may not be equal to each other. For example, suppose there are two connection requests: r_1 with setup time 00:00 and tear-down time 04:00, and r_2 with setup time 01:00 and tear-down time 02:00. Then the time is divided into three time slots $T_1(00{:}00\text{-}01{:}00)$, $T_2(01{:}00\text{-}02{:}00)$, $T_3(02{:}00\text{-}04{:}00)$. Time slot a is denoted by T_a, $a \in \{1, 2, 3, \ldots\ldots\}$. And $|T_a|$ denotes the duration of the time slot. The set of all time slots is denoted by $\boldsymbol{T}$.

The variables of the ILP are listed as follows:

- $V_{ij}^{T_a}$: number of lightpaths between node i and node j, in time slot T_a.
- V_{ij}^{w,T_a} : number of lightpaths between node i and node j using wavelength w, in time slot T_a.
- $P_{mn,T_a}^{ij,w}$: number of lightpaths between node i and node j routed through fiber link (m, n) using wavelength w, in time slot T_a.
- λ_{ij}^{r,T_a} : boolean variable which indicates whether connection request r is routed through a lightpath between node i and node j, in time slot T_a.
- $X_{k,T_a}^{ij,w}$: number of lightpaths between node i and node j routed through node k ($k \neq i, j$) using wavelength w, in time slot T_a.
- Y_k^{r,T_a} : boolean variable which indicates whether connection request r is routed through the intermediate node k ($k \neq$ the source and destination of r), in time slot T_a.

The objective of the ILP is to minimize the total energy consumption which comprises a traffic independent part and a traffic dependent part:

$$\sum_{T_a \in T} \{P_0 \sum_{ij} V_{ij}^{T_a} + p \sum_{ij} \sum_{r \in R} b_r \times \lambda_{ij}^{r,T_a}\} \times |T_a| \tag{2}$$

Subject to:

Virtual topology constraint:

$$\sum_{w} V_{ij}^{w,T_a} = V_{ij}^{T_a}, \forall i, j, T_a \tag{3}$$

Equation (3) ensures that the total number of lightpaths between node i and node j is the sum of the number of lightpaths on different wavelengths between the two nodes.

Wavelength routing constraints:

$$\sum_{n} P_{in,T_a}^{ij,w} = V_{ij}^{w,T_a}, \forall i, j, w, T_a \tag{4}$$

$$\sum_{m} P_{mj,T_a}^{ij,w} = V_{ij}^{w,T_a}, \forall i, j, w, T_a \tag{5}$$

Equation (4) and (5) are the flow conservation equations of the two ends of lightpaths.

$$X_{k,T_a}^{ij,w} \le V_{ij}^{w,T_a}, \forall i, j, w, T_a, k \neq i, j \tag{6}$$

Equation (6) ensures that the number of lightpaths going through an intermediate node using a particular wavelength is equal to or less than the total number of lightpaths between the two ends using that wavelength.

$$\sum_{m} P_{mk,T_a}^{ij,w} = 2 \times X_{k,T_a}^{ij,w}, \forall i, j, w, T_a, k \neq i, j \tag{7}$$

Equation (7) ensures that if a lightpath goes through an intermediate node, it would also goes through two neighboring fiber links of the intermediate node. Equation (6) and (7) are flow conservation equations of intermediate nodes of lightpaths.

$$\sum_{ij} P_{mn,T_a}^{ij,w} \le 1, \forall m, n, w, T_a \tag{8}$$

Equation (8) ensures that each wavelength in a fiber link can only be employed once.

Connection request constraints:

$$\sum_{j} \lambda_{sj}^{r,T_a} = 1, \quad \forall r, \forall T_a \text{ in the duration of } r. \tag{9}$$

$$\sum_{i} \lambda_{id}^{r,T_a} = 1, \quad \forall r, \forall T_a \text{ in the duration of } r. \tag{10}$$

Equation (9) and (10) are the flow conservation equations of the two ends of connection requests.

$$\sum_{r \in R} \lambda_{ij}^{r,T_a} \times b_r \le V_{ij}^{T_a} \times C, \forall i, j, T_a \tag{11}$$

Equation (11) ensures that the total bandwidth of all connection requests between two nodes is limited by the capacity of lightpaths between them.

$$\sum_{i} \lambda_{ik}^{r,T_a} = 2 \times Y_k^{r,T_a}, \forall r, T_a, \forall k \ne \text{the source or destination of } r. \tag{12}$$

Equation (12) ensures that if a connection request goes through an intermediate node, it would also goes through two neighboring virtual links of the intermediate node, which is a flow conservation equation of connection requests.

$$\lambda_{ij}^{r,T_a} = \lambda_{ij}^{r,T_b}, \text{ if } T_a \text{ and } T_b \text{ are both in the duration of } r. \tag{13}$$

Equation (13) ensures that each connection request would keep its route within its holding duration.

C. Illustrative Numerical Example

It is well known that traffic grooming problem is NP-complete. So we employ the small 6-node network shown in Fig. 1 to illustrate our formulation. Each link carries 2 wavelengths and each wavelength's capacity C is OC-48. There are totally four connection requests: r_1(0, 2, OC-12, 00:00, 04:00), r_2(2, 4, OC-12, 00:00, 03:00), r_3(0, 4, OC-3, 00:00, 02:00), r_4(2, 3, OC-3, 02:00, 04:00). We normalize $P_{max} = P_0 + p \times C = 1$. Take $P_0 = 0.25$. So $p = 0.75/48 = 0.015625$.

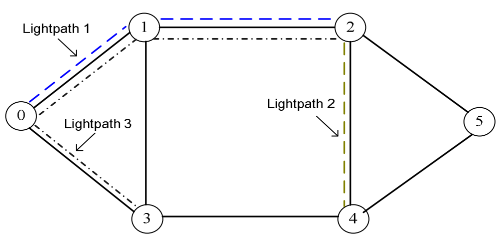

Fig. 1. Established lightpaths in the illustrative numerical example.

According to the setup and tear-down times of the four connection requests, there are totally 3 time slots: T_1(00:00-02:00), T_2(02:00-03:00), T_3(03:00-04:00). After solving the ILP, Fig. 1 shows the three lightpaths being established as well as their holding periods: Lightpath *1* between node *0* and node *2* (00:00-04:00); Lightpath *2* between node *2* and node *4* (00:00-03:00); and Lightpath *3* between node *2* and node *3* (02:00-04:00). And r_1 goes through Lightpath *1*, r_2 goes through Lightpath *2*, r_3 goes through both Lightpaths *1* and *2*, r_4 goes through Lightpath *3*, all in their respective requested holding times. In this example, the total energy consumption of establishing all connection requests is: 3.84375.

III. Dynamic Traffic Grooming with Time Awareness

In dynamic traffic grooming, connections arrive one at a time randomly and hold for the requested durations. The connection request is then represented by *r(s, d, b, h)*, where *h* denotes the requested holding time of the request. When a connection request arrives, the network operator should determine the route of this connection immediately. In this dynamic scenario, ILP is not feasible because of the real time requirement. Different kinds of heuristics have been proposed to solve the dynamic traffic grooming problem. The Novel Generic Graph Model proposed in [3] and the Grooming Graph Model proposed in [5] have similar layered structure and can achieve various objectives using different grooming policies by just adjusting the weights of the edges. In this paper, we adopt the Grooming Graph Model in [5] which is an undirected layered graph for simplicity. We employ this Grooming Graph to implement our newly proposed *TATG* algorithm, as well as the previously reported grooming policies such as *MinLP*, *MinHops* [4][10].

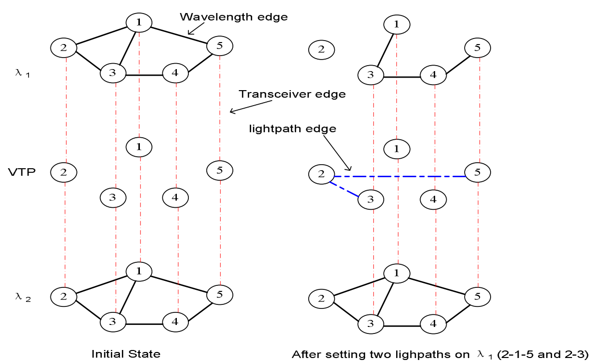

Fig. 2. Grooming Graph

The Grooming Graph has totally *W+1* planes, where *W* is the number of different wavelengths the network can support. Each wavelength is corresponding to a Wavelength Plane (*WP*) (λ_i, $1 \le i \le W$). And there is an additional plane called Virtual Topology Plane (*VTP*). The nodes in each plane correspond to the nodes in the physical topology. Fig. 2 shows the Grooming Graph for a 5-node network supporting 2 wavelengths, as an example.

There are three kinds of edges in the Grooming Graph:

Lightpath edge: there is a lightpath edge between two nodes in the *VTP* if there is a lightpath between the two corresponding physical nodes.

Wavelength edge: there is a wavelength edge between two nodes in the *WP* λ_i if there is fiber link between the two nodes and wavelength λ_i is free in this fiber link.

Transceiver edge: there is transceiver edge between the corresponding nodes in *VTP* and a *WP* if there is an unused transceiver. In this paper, we assume there are always enough wavelength tunable transceivers in each physical node. So, in our model, there are always transceiver edges between the corresponding nodes in *VTP* and a *WP*.

By adjusting the weights of these three kinds of edges, we can achieve various kinds of traffic grooming policies.

A. Time-Aware Traffic Grooming (TATG)

In order to save energy, according to [10], there is a tradeoff between minimizing the total number of lightpaths in the network and minimizing the average number of lightpaths (hops) the connection requests have gone through.

Intuitively, if we can groom a new connection request onto an existing lightpath with longer remaining holding time, we can reduce the number of lightpaths in the network. We illustrate the intuition by the following simple example.

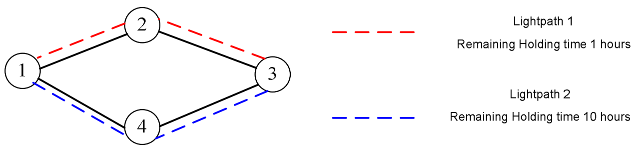

Fig. 3. Motivation Example

In Fig. 3, at certain moment, there are two existing lightpaths between node *1* and node *3*: Lightpath 1 with remaining holding time 1 hour and Lightpath 2 with remaining holding time 10 hours. At this moment, if a new connection request between node *1* and node *3* with requested holding time 4 hours arrives and both Lightpath 1 and Lightpath 2 have sufficient free bandwidth to accommodate the new request, intuitively, we should choose to groom the new request onto Lightpath 2 rather than Lightpath 1 or establish a new lightpath because we can minimize the number of lightpaths to 1 after Lightpath 1 being released 1 hour later.

On the other hand, we do not want the connection request to go through too many lightpaths (hops) in order to save energy.

The procedure of *TATG* is similar to the algorithms in [4] except that we adopt the following weight assignment for the three kinds of edges (14)-(16). When a connection request arrives, we can simply run the shortest-path algorithm (e.g., Dijkastra) between the two nodes in *VTP* corresponding to the two ends of the connection request on the Grooming Graph to derive the route of the new connection request, and then update the Grooming Graph. The selected route by the shortest-path algorithm determines whether we should establish new lightpaths and/or which existing lightpaths the new connection request should be groomed onto.

So in the proposed *TATG* algorithm, we adopt the following weight assignments to the three kinds of edges in Grooming Graph:

$$W_{lightpath} = \begin{cases} p \times b_r \times h, h \le H_l \\ p \times b_r \times h + P_0(h - H_l), h > H_l \end{cases} \tag{14}$$

$$W_{transceiver} = (P_0 + p \times b_r)h / 2 \tag{15}$$

$$W_{wavelength} = \delta \tag{16}$$

H_l is the remaining holding time of the corresponding lightpath which is decided by subtracting the current time from the latest tear-down time of the connection requests going through the lightpath; b_r is the requested bandwidth of the request; h, P_0, p have the same meanings as described before; δ is a very small real number (e.g., 0.00001). This weight assignment scheme assigns the actual newly induced energy consumption by each edge as its weight if the edge is chosen by the shortest-path algorithm. For example, in (14), if $h \le H_l$, the newly induced energy consumption of a lightpath is only the traffic dependent part. If $h>H_l$, the lightpath has to be sustained for an additional time duration of h-H_l, which would cause traffic independent energy consumption. In (15), a new lightpath would be established if two corresponding transceiver edges are chosen. So *TATG* minimize the newly increased energy consumption induced by each new connection request.

In order to compare the energy efficiency of different policies, *MinLP* [4] and *MinHops* (referred as *MinTHV* in [4] and *minT* in [10]) are also implemented by just adjusting the weights of the three kinds of edges:

MinLP: This policy tries to minimize the number of *newly* established lightpaths to carry the arriving connection request. To implement this policy, we configure the weight of transceiver edge much larger than that of lightpath edge. And the weight of lightpath edge is much larger than that of wavelength edge.

MinHops: This policy tries to minimize the number of hops (lightpaths or virtual links) the connection request goes through. To implement this policy, we configure the weight of transceiver edge just half of that of the lightpath edge. And both of their weights are much larger than that of the wavelength edge.

IV. SIMULATION RESULTS OF DYNAMIC TRAFFIC GROOMING

In this section, we compare the performance of different traffic grooming policies in terms of energy consumption, average number of hops and blocking probability under various traffic loads. The 24-node USNET shown in Fig. 4 is employed for the experiment. All the nodes are capable of traffic grooming but have no wavelength conversion capability. Each fiber link is bidirectional with 16 wavelengths and the capacity of each wavelength is OC-192. The traffic arrival process is Poisson process and the holding time is exponentially distributed with its mean value set to 1. All the connection requests are bidirectional and uniformly distributed among all the node pairs. There are four types of connection requests: OC-3, OC-12, OC-48 and OC-192, and the proportion of the number of these connection requests are 8:4:2:1. A connection request cannot be divided into several lower speed connections and routed separately. Each data point in the following figures is averaged over a total number of 50000 connection requests. In the energy consumption model, the maximum power consumption of a single lightpath is normalized to 1 and P_0 is set to 0.25 which is the same as in [10]. Other configuration of

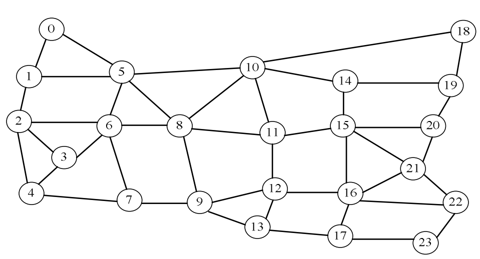

Fig. 4. 24-node USNET

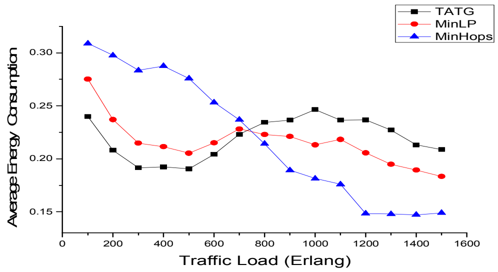

Fig. 5. Average energy consumption per connection

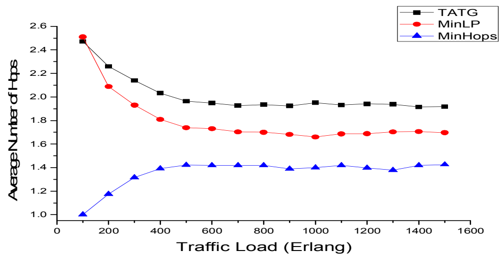

Fig. 6. Average number of hops (lightpaths) per connection goes through

P_0 ($0 \leqslant P_0 \leqslant 1$) would lead to similar conclusions as follows.

Fig. 5 shows the energy consumption of the three kinds of traffic grooming policies under various traffic loads. We observe that *TATG* achieves the least energy consumption when traffic load is relatively low and *MinHops* achieves the best performance when traffic load is relatively high. This is because, when traffic load is relatively low, *TATG* grooms traffic together as much as possible by trying to route new connection requests through the existing lightpaths with longer remaining holding time. On the contrary, *MinHops* tends to establish new lighpaths directly which induces unnecessary energy consumption. However, when traffic load is relatively high, this advantage of *TATG* diminishes because other policies also groom traffic together intensively in order to accommodate more traffic. In addition, when the traffic load is relatively high, the average number of hops plays an important role in determining energy consumption.

Fig. 6 shows the average number of hops (lightpaths) per connection request goes through if the three traffic grooming policies are applied. We observe that *MinHops* always achieves the least number of hops. When traffic load is relatively high, new lightpaths are hard to establish for all the three policies. If a connection request goes through more existing lightpaths (hops), the result is that more lightpaths has to carry the traffic of the new connection request and hold for a longer time period, leading to more energy consumption. So this is the reason why *MinHops* which tries to minimize the number hops consumes the least energy when traffic load is relatively high. In our configuration of *MinLP,* the weight of lightpath edge is much larger than that of wavelength edge, so *MinLP* also has an effect to minimize the number of hops, provided that the number of *newly* established lightpaths is minimized first.

Fig. 7 shows the blocking probabilities of the three kinds of traffic grooming policies. We observe that *TATG* achieves the lowest blocking probabilities and *MinHops* has the highest blocking probabilities. When traffic load is relatively high, the

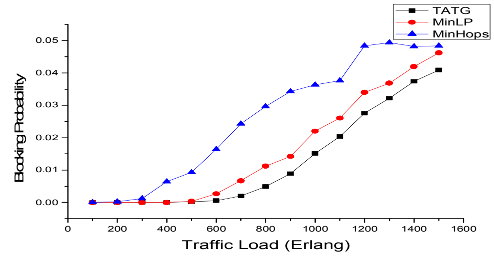

Fig. 7. Blocking probability

three policies would achieve similar blocking probabilities.

The simulation results provide implications to choose the most energy-efficient grooming policies under various traffic loads. We can adopt an adaptive scheme in which *TATG* is employed when traffic load is relatively low and *MinHops* is employed when traffic load is relatively high. The exact threshold of traffic load can be determined according to network topology and traffic characteristics, as in [4]. In our example, the threshold is about 700 Erlang.

V. Conclusion

Both static and dynamic time-aware traffic grooming problems are studied in order to reduce the energy consumption. Minimizing power consumption may not necessarily lead to minimizing energy. So time information is very important and should be taken into consideration in energy efficient design.

References

[1] J. Baliga, R. Ayre, K. Hinton, W. V. Sorin and R. S. Tucker, “Energy consumption in optical IP networks,” *J. Lightwave Tech.*, vol. 27, no. 13, pp. 2391-2403, 2009

[2] K. Zhu and B. Mukherjee, "Traffic grooming in an optical WDM mesh network," *IEEE J. Select. Areas Commun.*, vol. 20, pp. 122-133, 2002.

[3] H. Zhu, H. Zang, K. Zhu, and B. Mukherjee, “A novel, generic graph model for traffic grooming in heterogeneous WDM mesh networks,” IEEE/ACM Trans. Networking, vol. 11, pp. 285–299, 2003

[4] H. Zhu, H. Zang, K. Zhu, and B. Mukherjee, “Dynamic traffic grooming in WDM mesh networks using a novel graph model,” in *Proc. IEEE GLOBECOM*, pp. 2681 - 2685, 2002.

[5] H. Wen, L. Li R. He, Y. Yu, S. Sheng, N. Song, “Dynamic grooming algorithms for survivable WDM mesh networks,” *Photon. Netw. Commun.*, vol. 6, no. 3, pp. 253-263, 2003.

[6] M. Tornatore, A. Baruffaldi, H. Zhu, B. Mukherjee, A. Pattavina, “Dynamic traffic grooming of subwavelength connections with known duration,” in *Proc. OFC 2007.*

[7] B. Wang, T. Li, X. Luo, and Y. Fan, “Traffic grooming under a sliding scheduled traffic model in wdm optical networks,” in *Proc. of the 1st Workshop on Traffic Grooming in WDM Networks*, Oct. 2004.

[8] G. Shen and R. S. Tucker, “Energy-minimized design for IP over WDM networks,” *J. Opt. Commun. Netw.*, vol. 1, no. 1, pp. 176–186, 2009.

[9] S. Huang, D. Seshadri, R. Dutta, “A changing role in green optical Networks,” in *Proc. IEEE GLOBECOM*, NGNI-12, 2009.

[10] E. Yetginer, G. N. Rouskas, “Power efficient traffic grooming in optical WDM networks,” in *Proc. IEEE GLOBECOM*, ONS-07, 2009.

[11] M. Hasan, F. Farahmand, J. Jue, “Energy-awareness in dynamic traffic grooming,” in *Proc. OFC 2010*.

[12] M. Hasan, F. Farahmand, A. Patel, J. Jue, “Traffic grooming in green optical networks,” in *Proc. ICC 2010*.

[13] T. Li, B. Wang, C. Xin, X. Zhang, “On survivable service provisioning in WDM optical networks under a scheduled traffic model,” in *Proc. IEEE GLOBECOM*, PT02.2, 2005.

[14] S. Zhang, C. K. Chan, “Multicast protection in WDM optical networks with scheduled traffic,” in *Proc. ECOC*, paper p5.06, 2009.