Energy-Efficient Traffic Grooming in WDM Networks With Scheduled Time Traffic

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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 the static case, all connection requests with their setup and tear-down times are known in advance. We formulate an integer linear programming to minimize the energy consumption. In the dynamic case, we adopt a layered graph model called grooming graph and propose a new traffic grooming heuristics called time-aware traffic grooming, which takes the holding time of a new arrival connection request and the remaining holding time of existing lightpaths into consideration. We compare different traffic grooming policies, in terms of the energy efficiency, under various traffic loads. The results provide implications to select the most energy-efficient traffic grooming policies under various scenarios.**

***Index Terms*—Energy efficiency, traffic grooming, wavelength routing networks.**

I. Introduction

THE ENERGY consumption of Internet is quickly increasing with the traffic. According to [1], information and communication technology accounts for 2% of global carbon emission. Internet could consume 1% of the total electricity in broadband enabled countries [2]. These percentages are quickly rising. Hence, green networking has recently attracted much research attention. Power-aware traffic engineering approaches can realize more energy-efficient network systems, as well as reduce the operation expenditure of network service providers. In general, both the complexity and power requirements of most electronic systems do not scale well with the information density and data rate [3]. Their power consumption is almost linearly dependent on the throughput. In contrast, the power consumption of photonic systems is almost independent of the data rate, but grows mainly with the transmission interface circuitry. Hence, the role of optics is significant in reducing the energy consumption of Internet [3].

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Traffic grooming problem in optical wavelength routing network has been extensively studied with the aims to minimize the number of optical-electrical-optical (OEO) conversions, or maximize the total number of users served in the optical networks. Thus, the network bandwidth utilization can be optimized. In [4], a mathematical formulation of traffic grooming and several heuristics were proposed in order to improve the network throughput. In [5], 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 [4] and [5] dealt with static traffic grooming problem in which all connection requests were known in advance. In [6], the novel generic graph model in [5] was applied to a dynamic traffic grooming problem in which connection requests arrived at the network randomly. In [7], a layered grooming graph was proposed to investigate the survivable traffic grooming algorithms. In [8], the holding time information of connections was exploited to improve the traffic grooming performance in terms of blocking probability. In [9], 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.

Traffic grooming requires electrical multiplexing and OEO conversion, which induce much energy consumption. Recently, there has been a growing interest in achieving energy-efficient traffic grooming. In [10], both mixed-integer linear programming and heuristics were reported to solve the energy-minimized static traffic grooming problem for IP over wavelength division multiplexing Networks. In [11], two different model formulations, namely flow based and interface based, were proposed to model the power consumption in optical networks. The work in [12] adopted the interface-based formulation and formulated an integer linear programming (ILP) for the traffic grooming problem, so as to minimize the power consumption. In [13], a more detailed energy consumption model considering the modular structure of optical network nodes was presented to solve the dynamic traffic grooming problem. In [14], the authors adopted the same interface-based power model as in [11] and a layered auxiliary graph to route the connection requests. However, they did not consider the impact of time awareness on energy consumption.

As far as we know, most existing works on energy-efficient traffic grooming do not consider *time information*, which is a very crucial factor in energy saving, as energy consumption is the product of power and time. Hence, minimizing the power consumption does not necessarily lead to minimizing the energy consumption. In view of this, we have recently performed preliminary studies in both static and dynamic energy-efficient

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traffic grooming problems with an additional consideration of time information [15]. In this paper, we further extend this work by providing more comprehensive simulation results and discussions in system parameter characterization. Based on the results, we provide implications of the optimal strategies to achieve time-aware energy-efficient traffic grooming.

The rest of this paper is organized as follows. In Section II, we introduce the power consumption model assumed in this study. In Section III, the ILP formulation for the time-aware static traffic grooming is introduced. In Section IV, new time-aware traffic grooming (TATG) heuristics is proposed for dynamic scenario. In Section V, simulation results are presented to compare the performance of different traffic grooming policies. Section VI concludes this paper.

II. Power Consumption Model

We adopt the interface-based formulation in [11] as the power consumption model. In this model, it was assumed that the main power consumption components in optical network were the ports of digital cross connect (DXC), IP routers, multiprotocol label switching equipment, as well as OEO conversions. This is justified by the fact that line cards of DXC are typically responsible for electronic switching and OEO conversions. Without losing generality, this is a simplified model compared to the one presented in [13], in which a more detailed modular structure (chassis, line card, and transceiver) of optical network nodes was considered. In interface-based formulation, since all the main power consumption components are at the interfaces of lightpaths, the power consumption of the whole network is calculated as the sum of the power consumption of individual lightpaths, each of which is assumed to have a linear dependence with the amount of traffic and is represented as

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

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 that denotes the power consumption per additional unit traffic. b_l denotes the amount of traffic carried on the lightpath l. It is also assumed that the inactive components (e.g., transceivers) 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 study adopts interface-based formulation for simplicity, our following formulation and algorithms are applicable to other power consumption models by just modifying the objective function of the ILP formulated in the static traffic grooming and modifying the grooming graph in the dynamic case.

III. 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 [16] and [17]. 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

With all the connection requests known in advance, the static energy-efficient traffic grooming turns out to be a mathematical optimization problem. The network topology $\boldsymbol{G} = (\boldsymbol{V}, \boldsymbol{E})$ is given as an undirected graph. $\boldsymbol{V}$ is the set of network nodes capable of traffic grooming. $\boldsymbol{E}$ is the set of bidirectional fiber links (each link in $\boldsymbol{G}$ represents a single bidirectional fiber). 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. So 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 $T_1(00:00{-}01:00)$, $T_2(01:00{-}02:00)$, and $T_3(02:00{-}04:00)$. 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.

1) $V_{ij}^{T_a}$: number of lightpaths between node i and node j, in time slot T_a.
2) V_{ij}^{w,T_a}: number of lightpaths between node i and node j using wavelength w, in time slot T_a.
3) $P_{mn,T_a}^{ij,w}$: number of lightpaths between node i and node j routed through fiber link (m, n) using wavelength w, in time slot T_a. It is a Boolean variable.
4) λ_{ij}^{r,T_a}: Boolean variable that indicates whether connection request r is routed through a lightpath between node i and node j, in time slot T_a.
5) $X_{k,T_a}^{ij,w}$: 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.
6) Y_k^{r,T_a}: Boolean variable that 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:

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

subject to

Virtual topology constraint:

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

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:

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

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

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

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

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, so eliminates any looped path:

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

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

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

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

Connection request constraints:

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

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

Equation (9) and (10) are the flow conservation equations of the two ends of connection requests. s and d are the two ends of the connection request r, respectively,

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

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

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

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

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

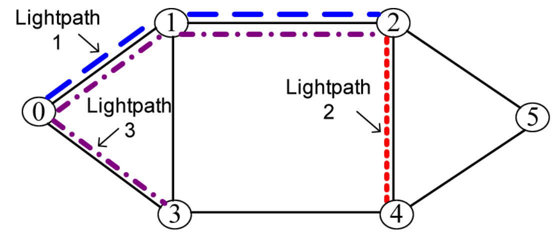

Fig. 1. Established lightpaths in the illustrative numerical example.

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. We employ the small six-node network shown in Fig. 1 to illustrate the correctness of our formulation. Each link carries two 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), and 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, $p = 0.75/48 = 0.015625$.

According to the setup and tear-down times of the four connection requests, there are totally three time slots: T_1 $(00:00{-}02:00)$, T_2 $(02:00{-}03:00)$, and 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; and r_4 goes through Lightpath 3. All the connections are established in their respective requested holding times. In this example, the total energy consumption of establishing all connection requests is 3.84375. As a comparison, if each of the four connection requests is established directly between the two ends using a lightpath and holds for the corresponding requested duration, the total energy consumption would be 4.25.

IV. 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 [5] and the grooming graph model proposed in [7] 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 [7] which is an undirected layered graph. We employ this grooming graph to implement our newly proposed TATG algorithm, as well as the previously reported grooming policies such as *MinLP*, *MinHops* [6], [12].

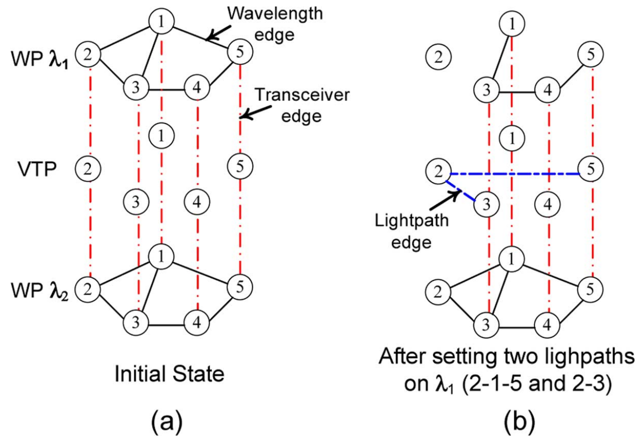

Fig. 2. (a) and (b) Example of a grooming graph. WP: wavelength plane, VTP: virtual topology plane, black solid line: wavelength edge, red dotted line (—·—): transceiver edge, blue dotted line (----): lightpath edge.

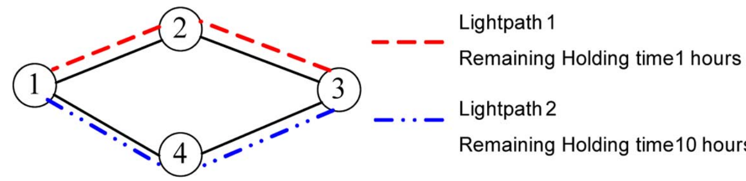

Fig. 3. Motivation example.

Algorithm 1: Time Aware Traffic Grooming (*TATG*)

Initialization:

Construct the Grooming Graph according to the initial network state.

When a connection request *r(s, d, b, t_s, t_e)* arrives:

1. Assign the corresponding weights to edges in the Grooming Graph and then run the shortest-path algorithm (e.g., Dijkastra) between the two nodes in *VTP* corresponding to *s* and *d* respectively. If the path is not found, block the connection request; otherwise, continue with the following steps.
2. Route *r* according to the found path: If the path contains transceiver edge(s) or wavelength edge(s), establish corresponding new lightpath(s); if the path contains lightpath edge(s), route the connection request along the existing lightpath(s).
3. Update the network state and the Grooming Graph.

When a connection request terminates:

1. Tear down all the lightpaths carries no traffic.
2. Update the network state and the Grooming Graph.

Algorithm: TATG.

The grooming graph [7] has totally $W+1$ planes, where W is the number of different wavelengths supported in the network. One distinct wavelength plane (WP) $(\lambda_i, 1 \leq i \leq W)$ is assigned to each supported wavelength. An additional virtual topology plane (VTP) is assigned to record the established lightpaths. The nodes in each plane correspond to the nodes in the physical topology. Fig. 2(a) shows the grooming graph for a five-node network supporting two wavelengths, as an example, when no lightpath is established. There are three kinds of edges in the grooming graph. A *lightpath edge* between two nodes on the VTP indicates a lightpath established between the two corresponding physical nodes. A *wavelength edge* between two nodes on the $WP\lambda_i$ indicates that there exists a fiber link between the two nodes, and wavelength λ_i is free in this fiber link. A *transceiver edge* connecting the same node on VTP and a *WP* indicates an unused transceiver available. 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 connecting among the same nodes on VTP and all WPs. Fig. 2(b) illustrates a simple example when two lightpaths (2-1-5) and (2-3) are established. In this case, two lightpath edges (2-5), (2-3) are added to the VTP, while the wavelength edges (2-1), (1-5), and (2-3) are removed on WP λ_1, as they have been used in the two established lightpaths. By making use of this grooming graph, various kinds of traffic grooming policies can be achieved by assigning appropriate weights to these three kinds of edges, individually.

A. TATG

In order to save energy, according to [12], 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 go through. This is because energy consumption of a lightpath depends on two parts: traffic-independent (fixed) part and traffic-dependent part.

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.

In Fig. 3, at certain moment, there are two existing lightpaths between node 1 and node 3: Lightpath 1 with remaining holding time 1 h and Lightpath 2 with remaining holding time 10 h. At this moment, if a new connection request between node 1 and node 3 with requested holding time 4 h 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 h 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 [6] except that we adopt the following weight assignment for the three kinds of edges (14)–(16). The TATG procedure is shown in Algorithm 1. When a connection request arrives, we can simply run the shortest path algorithm (e.g., Dijkastra) between the two nodes on 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.

In the proposed TATG algorithm, we adopt the following weight assignment, $a_{\text{lightpath}}$, $a_{\text{transceiver}}$, and $a_{\text{wavelength}}$ to the lightpath edge, the transceiver edge and the wavelength edge, respectively, in grooming graph:

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

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

$$a_{\text{wavelength}} = \delta \tag{16}$$

where H_l is the remaining holding time of the existing lightpath, which is determined by subtracting the current time from the latest tear-down time of the existing connection request going through the lightpath; h is the holding time of the new request, b_r is the requested bandwidth of the new request; P_0 and p have been defined in the power consumption model; and δ is a very small real number (e.g., 0.00001). With this weight assignment scheme, whenever an edge is chosen by the shortest path algorithm, its weight would be assigned as the actual newly induced energy consumption by that edge. In (14), if $h \le H_l$, the new request would be groomed to the existing lightpath, and the newly induced energy consumption to that lightpath is only due to the traffic-dependent part. However, if $h > H_l$, the existing lightpath has to be sustained for an additional time duration of $(h - H_l)$, which would cause traffic-independent energy consumption, in addition to its traffic-dependent part. In (15), a new lightpath would be established if two corresponding transceiver edges are chosen. In this way, TATG minimizes the newly increased energy consumption induced by each new connection request.

In order to compare the energy efficiency of different policies, *MinLP* [6] and *MinHops* (referred as *MinTHV* in [6] and *minT* in [12]) 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.

V. Simulations 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 and the 15-node Pacific Bell Network shown in Fig. 5 are employed in the simulations. All the nodes are capable of traffic grooming but have no optical 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 50 000 connection requests. In the energy consumption model, the maximum power consumption of a single lightpath is normalized to 1 and P_0 is first set to 0.25 which is the same as in [10]. Other configuration of $P_0 (0 \le P_0 \le 1)$ and traffic distributions would lead to similar conclusions which would be also be illustrated in the Section V-A.

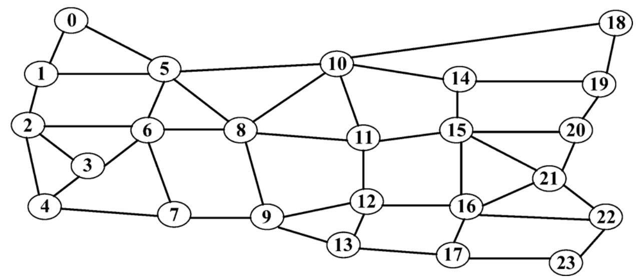

Fig. 4. 24-node USNET.

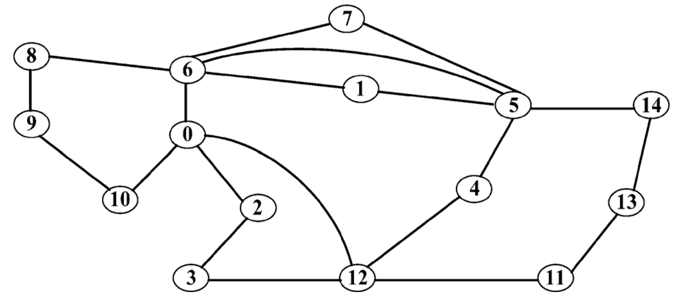

Fig. 5. 15-node Pacific Bell Network.

Figs. 6 and 7 show the energy consumption of the three kinds of traffic grooming policies under various traffic loads in 24-node USNET and 15-node Pacific Bell Net, respectively. From both figures, 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, which would be illustrated as follows.

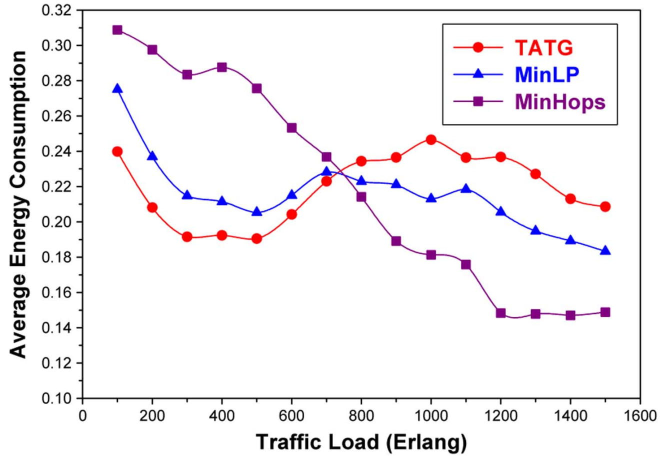

Fig. 6. USNET: average energy consumption per connection.

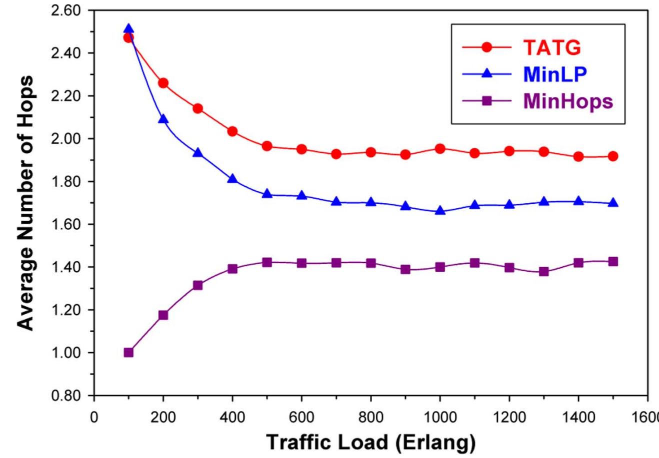

Fig. 8. USNET: average number of hops (lightpaths) per connection.

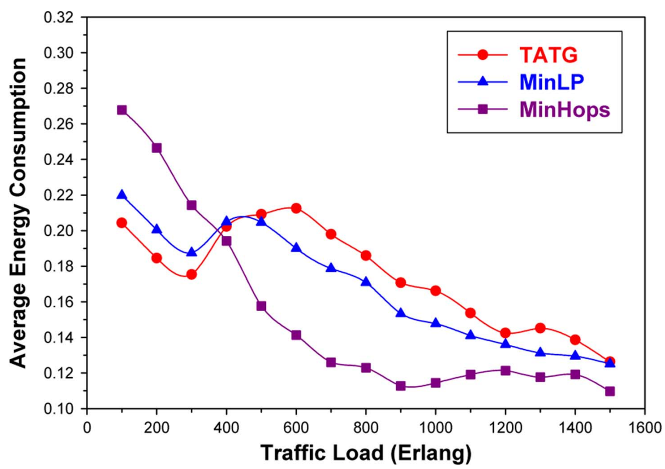

Fig. 7. Pacific Bell Net: average energy consumption per connection.

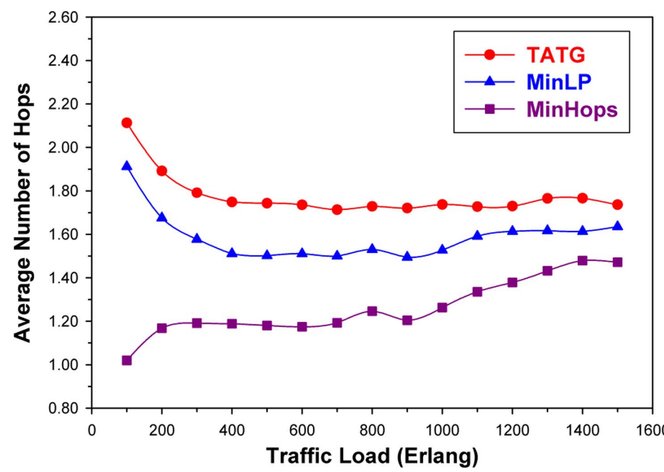

Fig. 9. Pacific Bell Net: average number of hops (lightpaths) per connection.

Figs. 8 and 9 show the average number of hops (lightpaths) per connection request goes through if the three traffic grooming policies are applied in 24-node USNET and 15-node Pacific Bell Net, respectively. From both figures, 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 have to carry the traffic of the new connection request and must hold for a longer time period, leading to more energy consumption. So, this is the reason why *MinHops* that 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.

Figs. 10 and 11 show the average number of wavelength links per established lightpath in 24-node USNET and 15-node Pacific Bell Net, respectively. In the two topologies, we observe that *MinHops* achieves the minimum. It means that the average length of the lightpaths established by *MinHops* is the shortest among the three policies. The connections established by TATG and *MinLP* would rather go through several existing long lightpaths than establishing a new and short lightpath. Combined with the results shown in Figs. 8 and 9 that *MinHops* always achieves the minimum number of Hops (lightpaths), it can be inferred that *MinHops* is the best choice for network operators if most users require very low packet delay.

Figs. 10 and 11 also show the blocking probabilities of the three kinds of traffic grooming policies. From both figures, we observe that TATG achieves the lowest blocking probabilities and *MinHops* has the highest blocking probabilities when traffic load is low. When traffic load is relatively high, the three policies would achieve similar blocking probabilities.

A. *Alternative Configuration of Simulation Parameters*

In this section, we will show the simulation results of energy consumption performances under alternative simulation configurations. We employ the 15-node Pacific Bell network shown in Fig. 5 as an example.

Figs. 12–14 show the energy consumption of the three kinds of traffic grooming policies under various traffic loads if P_0 is set to 0, 0.76 and 1, respectively. The maximum power consumption of a single lightpath is still normalized to 1. From Fig. 12, we can observe that when $P_0 = 0$, TATG is actually the same as *MinHops*. This is because when $P_0 = 0$, the induced energy consumption of each new connection is only decided by the number of hops (lightpaths) it would go through. In this case, the holding

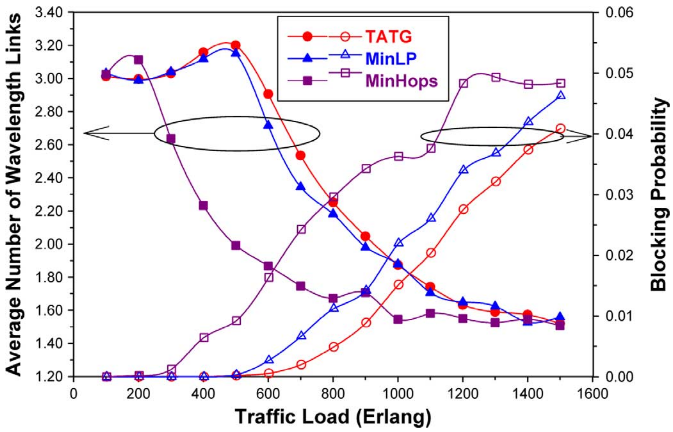

Fig. 10. USNET: average number of wavelength links (left axis), and blocking probability (right axis).

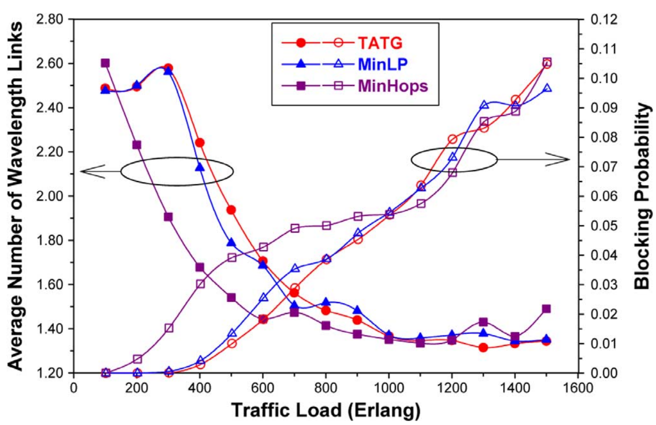

Fig. 11. Pacific Bell Net: average number of wavelength links (left axis), and blocking probability (right axis).

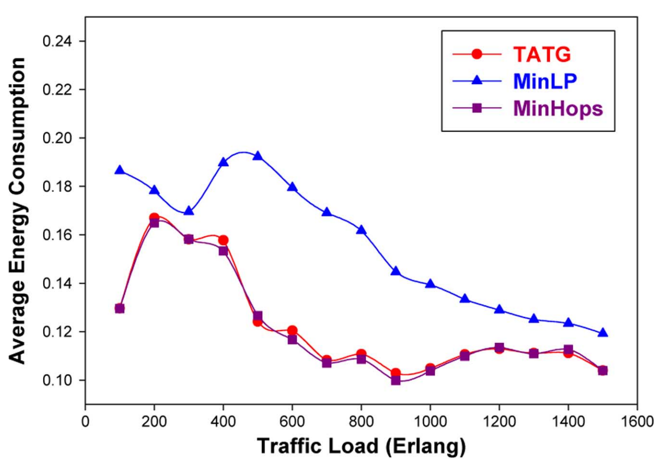

Fig. 12. Pacific Bell Net: average energy consumption per connection $P_0 = 0$.

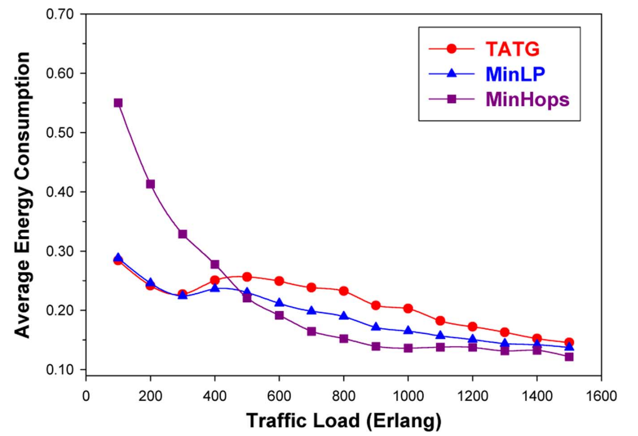

Fig. 13. Pacific Bell Net: average energy consumption per connection $P_0 = 0.76$.

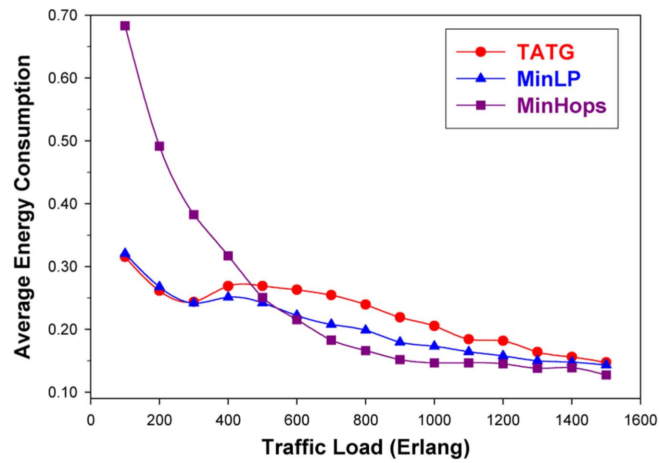

Fig. 14. Pacific Bell Net: average energy consumption per connection $P_0 = 1$.

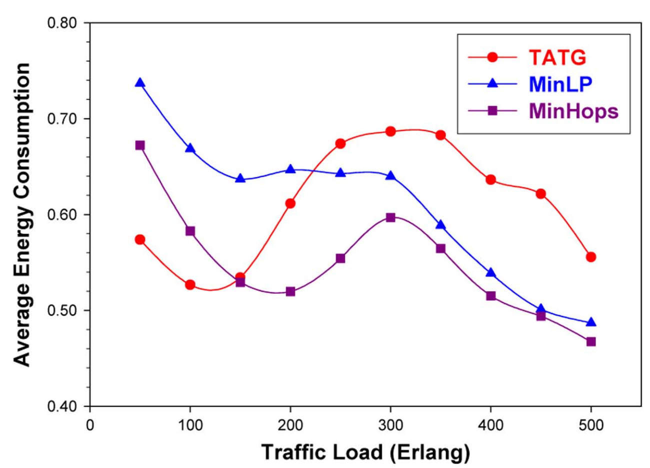

Fig. 15. Pacific Bell Net: average energy consumption per connection when $P_0 = 0.76$ and connections uniformly distributed between OC-1 and OC-96.

times of existing lightpaths no longer matters. When $P_0 = 0$, this can be verified from the weight assignments scheme [see (14)–(16)] that the weight of transceiver edge is just half of that of the lightpath edge and both of their weights are much larger than that of the wavelength edge, which is just the same as *MinHops*. From Figs. 13 and 14, we can observe that as P_0 is approaching 1, *MinHops* performs much worse than the other two grooming policies when traffic load is relatively low. This is because the main energy consumption is due to the newly established lightpaths. When traffic load is low, *MinHops* would rather establish new lightpaths than going through several existing lightpaths to reduce the hop distances. Similar to the reasons for $P_0 = 0.25$, when traffic load is relatively high, *MinHops* still achieves the best performance among the three policies because the average number of hops plays an important role in finding the energy consumption when traffic load is high. Fig. 15 shows the performance when $P_0 = 0.76$ and the granularity of the requested bandwidth of a connection is uniformly distributed between OC-1 and OC-96. (The traffic load of 500 Erlang is relatively large as the blocking probability is around 30% under this traffic load). We can still observe that TATG performs the best when traffic load is relatively low, and *MinHops* achieves the best performance among the three policies when traffic load is relatively high. According to the simulation results under different parameter configurations, implications can be provided to choose the most energy-efficient grooming policies under various traffic loads. It would be desirable to adopt an adaptive scheme in which TATG is employed when traffic load is relatively low, while *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.

VI. Summary

Both static and dynamic TATG problems are studied in order to reduce the energy consumption. Minimizing power consumption may not necessarily lead to minimizing energy consumption. So, time information is very important and should be taken into consideration in energy-efficient design. According to the simulation results, TATG can achieve the least energy consumption when traffic load is relatively low, and *MinHops* can achieve the least when traffic load is relatively high. In this paper, energy-efficient traffic grooming is considered under the assumption that the provisioning durations of the connection requests are only determined by the users' requests. If network operators could schedule the connection requests properly according to traffic load conditions, better energy efficiency may be achieved.

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