Dynamic Energy-aware Multipath Grooming

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Abstract—This paper investigates the use of multipath grooming to save energy in Wavelength Division Multiplexing (WDM) networks by splitting the bandwidth demand of requests among several paths and aggregating them with already established lightpaths. For that, two algorithms are proposed which employ an auxiliary graph whose edge weights represent the energy consumed by all the operations related to the optical transmission in a lightpath to provide the bandwidth requested. Both algorithms select a subset of different sets of \( k \) lightpaths in which residual bandwidth surpasses minimally the demanded bandwidth with minimum energy consumption. These two algorithms represent the choice of criteria between energy consumption only or both energy and bandwidth. It is shown that the algorithm which considers both energy and bandwidth employs a lower number of lightpaths while reducing the energy consumption and blocking rate.

I. INTRODUCTION

In recent years, telecommunication companies (telcos) and Internet Service Providers (ISPs) have faced an increase in energy consumption due to the growing spread of broadband access and the expansion of the services offered. According to Bolla et al. [1], the increase in the volume of the network traffic follows the Moore’s law, doubling every 18 months; while silicon technologies improve their energy efficiency according to the Dennard’s law, by a factor of 1.65 every 18 months. Thus, there is a constant increase in energy consumption related to communication networks, which corresponds to 2\% to 10\% of the world current energy consumption and this is expected to increase in the coming years. Such growth has motivated telcos and ISPs to operate their networks more efficiently, without compromise the service offered.

By exploring the residual capacity of already established lightpaths, traffic grooming offers the potentiality to reduce the energy consumption by avoiding the overhead resulted from the allocation of lightpaths. Additionally, such overhead can also be avoided by splitting and transmitting a single request for connection establishment into multiple parallel lightpaths (multipath routing), if the sum of the residual bandwidths of these lightpaths is at least equal to the bandwidth demand of the request. Moreover, dynamic traffic grooming and multipath routing can be jointly employed to serve both applications that demand supra-wavelength bandwidth and those demanding sub-wavelength bandwidth. Leveraging the use of these two techniques, also known as multipath grooming, increases the potentiality of efficient utilization of the residual capacity of existing lightpaths and the reduction on the creation of new lightpaths.

This paper investigates the use of multipath grooming to save energy in network operation by splitting the bandwidth demand of requests among several paths which are aggregated with already established lightpaths. For that, two algorithms are proposed. They employ an auxiliary graph whose edge weights represents the total energy consumed by all the operations related to the optical transmission on a lightpath. Both algorithms select a set of \( k \) potential lightpaths (edges) to provide the bandwidth requested. One of them selects the \( k \) paths with the least energy consumption whereas the other selects a set of \( k \) paths which has sufficient residual bandwidth to support the request. Both algorithms select a subset of different sets of \( k \) lightpaths in which residual bandwidth surpasses minimally the demanded bandwidth with minimum energy consumption. These two algorithm represent the choice between energy consumption only and both energy consumption and bandwidth. It is shown that the algorithm which considers both energy and bandwidth employs a lower number of lightpaths, which reduces both energy consumption and blocking.

Simulations involving dynamic scenarios showed that multipath grooming outperforms its single path counterpart. It is our best knowledge that these are the first energy-aware algorithms based on multipath traffic grooming proposed so far.

This paper is organized as follows. Section II overviews related work. Section III describes the employed energy consumption model. Section IV introduces the proposed energy-aware multipath grooming algorithms. Section V presents a numerical evaluation of the proposed algorithm. Section VI concludes the paper.

II. RELATED WORK

Motivated by economical and environmental reasons, network operations which promote energy saving has attracted the attention of the research community. Bianzino et al. [2] surveyed potential directions of green networking. In [3] and [4], efficient operation for energy saving of optical networks was surveyed.

Xia et al. [5] proposed an energy-aware algorithm for WDM networks that captures the energy consumption. The accountability of energy consumption of lightpaths in WDM networks was also considered in an ILP (Integer Linear Programming) based solution for the grooming problem with static traffic scenario [6].

In [7], a dynamic energy-aware traffic grooming algorithm for WDM networks was investigated considering a reduced auxiliary graph, which limits the space of solutions and captures the energy consumption of lightpath provisioning.

The minimization of energy consumption in optical networks was also investigated considering the knowledge of the duration of the connections [8], [9]. In [10], an algorithm was
proposed to take into account classes of services related to energy consumption.

In another thread of research, multipath based on ILP has been proposed to cope with supra-wavelength requests, which does not consider energy aspects [11]. Lee et al. [12] presented a multipath algorithm for energy saving, which is not specific to optical networks. The idea is to design a topology using Steiner trees for static traffic scenarios employing both singlepath and multipath routing solutions derived from a modified bin-packing problem.

The algorithm proposed in the present paper aims to groom requests on multiple parallel lightpaths (multipath). Differently than the work in [12], decisions about the adoption of multiple lightpath consider in detail the energy consumption of operations related to data transmission in WDM networks. Moreover, the present work addresses scenarios in which requests arrive and depart dynamically.

III. ENERGY CONSUMPTION MODEL

The energy consumption model used in this paper follows that introduced in [5]. According to this model, the energy consumption of an IP/MPLS over WDM network is calculated by adding the energy consumption of a set of operations related to data transport in the network which includes: electronic switching (ES), optical switching (OS), electro-optical conversion (EO), optical-electronic conversion (OE), transponder transmission (TX), transponder reception (RX), and signal amplification (AM). For each operation, the energy consumption is given by:

\[ P = P_O + P_T \times t \]  

where \( P_O \) and \( P_T \) are, respectively, the fixed and the traffic-dependent parameters of the consumption of the operation, and \( t \) the carried traffic.

An example in Figure 1 is given to illustrate the energy consumption of a lightpath establishment. In this figure, there are four pairs of IP/MPLS router and OXC. There are two lightpaths \( L_1 \) and \( L_2 \) with routes \( A \rightarrow A' \rightarrow B' \rightarrow C' \rightarrow C \) and \( C \rightarrow C' \rightarrow D' \rightarrow D \), respectively, and two IP/MPLS flows \( F_1 \) and \( F_2 \), from \( A \) to \( C \) and from \( A \) to \( D \), respectively. Flow \( F_1 \) is directly carried by lightpath \( L_1 \) while flow \( F_2 \) is carried from \( A \) to \( C \) by lightpath \( L_1 \) and from \( C \) to \( D \) by lightpath \( L_2 \).

Without loss of generality, in Equation 1, both the term independent of the traffic load and the dependent one can be associated to the establishment of lightpaths and to their carried flows, respectively. Thus, the energy consumption of the lightpath \( L_1 \) can be calculated by adding each term that is independent of the traffic \( (P_O) \) for each operation involved in the transmission using the lightpath \( L_1 \). These operations are: electronic switching at \( A \), electro-optical conversion from \( A \) to \( A' \), optical switching and transponder transmission at \( A' \), the signal amplification from \( A' \) to \( B' \), optical switching at \( B' \), the signal amplification from \( B' \) to \( C' \), transponder reception and optical switching at \( C' \), optical-electronic conversion from \( C' \) to \( C \) and electronic switching at \( C \).

For the lightpath \( L_2 \), the energy consumption can be computed as the sum of: the electronic switching at \( C \), the electro-optical conversion from \( C \) to \( C' \), the optical switching and transponder transmission at \( C' \), the signal amplification from \( C' \) to \( D' \), the transponder reception and optical switching at \( D' \), the optical-electronic conversion from \( D' \) to \( D \) and the electronic switching at \( D \).

For the flow \( F_1 \), the energy consumption can be computed by the same operations used in the computation of the energy consumption of the lightpath \( L_1 \), and by using the traffic-dependent term of the energy consumption operations \( (P_T \times t) \), where \( t \) is the bandwidth of the flow \( F_1 \).

For the flow \( F_2 \), the energy consumption can be computed by accounting the same operations accounted in the computation of the energy consumption of lightpaths \( L_1 \) and \( L_2 \) minus an electronic switching operation. The latter needs to be subtracted since both lightpaths \( L_1 \) and \( L_2 \) consider an electronic switching operation at node \( C \), and indeed there is only one electronic switching operation at node \( C \) that is due to the electronic conversion from the lightpath \( L_1 \) to the lightpath \( L_2 \). Similarly to the flow \( F_1 \), the traffic-dependent term of the energy consumption operations \( (P_T \times t) \), where \( t \) is the bandwidth of the flow \( F_2 \) is computed.

Note that the smaller the traffic load in a lightpath, the greater is the impact of component independent of the traffic load. Thus, greater efficiency can be achieved by aggregating IP/MPLS flows onto existing lightpaths. Nevertheless, aggregating the traffic using multi-hop lightpaths requires a larger number of electronic switching and signal conversion operations, which can consume more energy than the energy needed to establish a new single-hop lightpath to carry the traffic.

IV. ALGORITHMS FOR DYNAMIC ENERGY MULTIPATH GROOMING

The algorithms proposed in this section aim to make decisions on lightpath provisioning to requests that arrive dynamically. A request \( r \) is defined as \( r = (s, d, b) \), where \( s \) is the source node, \( d \) the destination node, and \( b \) the requested bandwidth.

Connections that can not be provisioned in a single lightpath due to the unavailability of bandwidth are split and transmitted over multiple lightpaths (multipath), if the sum of the residual bandwidth in these lightpaths is at least equal to the requested bandwidth \( b \).
The proposed algorithms, called Energy-aware Multipath Grooming Algorithm (EM) and Energy and Bandwidth aware Multipath Grooming (EBM), take advantage of the fact that splitting connections on multiple lightpaths can increase the number of requests accepted as well as reduce the establishment of new lightpaths.

Both algorithms consider an auxiliary graph \( G \) to represent existing and potentially allocable lightpaths. Both algorithms select a set of \( k \) lightpaths for potential provisioning of requests for connection establishment. The EM algorithm selects the \( k \) lightpaths with least energy consumption whereas the EBM selects a set of \( k \) lightpaths which has residual bandwidth equal or larger than the requested demand and which has the least energy consumption. \( k \) is the maximum number of lightpaths that can be allocated to provide the bandwidth to a request. The algorithm select a subset of the chosen \( k \) lightpaths which has sufficient residual bandwidth to provide the bandwidth demand.

### A. Multipath Grooming Algorithms

Both algorithms are executed at the arrival of a request. In the EM algorithm (Algorithm 1), if there exist lightpaths with sufficient bandwidth for the provisioning of the demanded request, the lightpath with the least energy consumption is selected (Lines 1-3).

#### Algorithm 1 Energy-Aware Multipath Grooming (EM)

**Input:** Demand \( r(s, d, b) \) requesting \( b \) bandwidth units between \((s, d)\)

**Output:** Set of lightpaths between \( s \) and \( d \) to aggregate \( r \)

1. **if** There is a set of lightpaths \( l \) \( \forall l \ B(l) \geq \ b \) **then**
2. Construct \( G \) with this set of \( l \)
3. Return \( l \) with lowest cost to aggregate \( r \)
4. **else**
5. Construct the auxiliary graph with \( l \) \( \forall l \ B(l) > 0 \)
6. Compute the cost of candidate lightpaths \( l \) using Eq. 1
7. Select the \( k \) paths with least energy consumption
8. Enumerate all possible combination of subsets \( [C^k_i] \)
9. Return the subset of lightpaths in \( [C^k_i] \) with the lowest cost and which \( \sum_{j=1}^{\ k} B(l_j) \) is minimal

10. **end if**

If there is no single lightpaths with sufficient residual bandwidth to accommodate the connection request, the connection is served by a subset of lightpaths among the set of \( k \) paths with the least energy consumption and which residual bandwidth exceeds minimally the demand.

In the first step, the EM algorithm construct an auxiliary graph (Line 5). For each edge in the graph representing a lightpath, a cost is associated to represent the energy consumption (Line 6). The \( k \) lightpaths with lowest costs are selected (Line 7). Then, all possible combinations of lightpaths are enumerated (Line 8). Finally, the subset of lightpaths with the lowest cost and that has the minimum residual bandwidth exceeding the bandwidth demand is selected (Line 9).

The Energy and Bandwidth aware Multipath Grooming algorithm (EBM) differs from the EM by Line 5 which is:

5: Construct the auxiliary graph with \( l \) \( \forall l \ B(l) \geq \ b/k \)

Thus, in the EBM algorithm the auxiliary graph contains only edges that have at least \( b/k \) available bandwidth. The idea is to select a set of lightpaths that satisfies the bandwidth demand of the request and consequently increases the chances of selecting a low number of lightpaths. As in the EM algorithm, all the combinations of \( i \) lightpaths \( [C^k_i] \) are enumerated and the subset of lightpaths with least energy consumption and minimum aggregated bandwidth exceeding the requested bandwidth.

The construction of the auxiliary graph involves \( O(N^2) \) operations, where \( N \) is the number of nodes in the network (Lines 2 and 5). The cost computation in Line 6 is applied to each lightpath/edge in the graph, thus its complexity is \( O(E) \). To find the path with the lowest cost, Dijkstra requires \( O(N^2) \) operations (Line 3). The selection (Line 7) requires \( k \) executions to find the \( k \) paths with least energy consumption, then it demands \( k \times O(N^2) \) operations. Thus, the complexity of the algorithm is \( O(N^2) \).

### B. Energy-Aware Singlepath Grooming Algorithm

To assess the advantage of employing the energy-aware multipath grooming, singlepath algorithm was defined (Algorithm 2).

Upon arrival of a connection request \( r = (s, d, b) \), the auxiliary graph \( G \) is constructed by including lightpaths \( l \) with residual capacity \( B(l) \) equal or greater than the required bandwidth \( b \) (Line 1). In Line 2, the cost of each edge in \( G \) is the energy consumption of the corresponding singlepath. The lightpath with the least energy consumption \( r \) is then chosen (Line 3).

#### Algorithm 2 Energy-Aware Singlepath Grooming

**Input:** Demand \( r(s, d, b) \) requesting \( b \) bandwidth units between \((s, d)\)

**Output:** Feasible path between \( s \) and \( d \) to aggregate \( r \)

1. Construct the auxiliary graph \( | \forall l \in G \ B(l) \geq \ b \)
2. Compute the cost of candidate lightpaths \( l \) according to Eq. 1
3. Choose the lightpath \( l \) with the lowest energy consumption

### V. PERFORMANCE EVALUATION

To assess the performance of the proposed algorithms, simulations were conducted and results compared to those given by the singlepath algorithm. The RWA algorithm employed a single-hop Fixed-Alternate Routing with 5 alternative routes. The First-Fit wavelength assignment was used.

Simulations were performed using the WDMSim [13] simulator and the independent replication method was employed to generate confidence intervals with 95% confidence level. Each simulation run involved 1 million connection requests. The NSF topology, with 16 nodes and 25 bidirectional links (Fig. 2) was used. Each fiber carries 16 wavelengths, with bandwidth capacity of an OC-192 carrier (10 Gbps); each node is
a multi-hop partial grooming node with 32 grooming port pairs (input/output) and no wavelength-conversion capability. The number of in-line amplifiers for each link is given by \[ \left[ \frac{S_e}{801} \right] + 2 \] [14], where \( S_e \) is the length of the link \( e \) in kilometers.

Connections arrive according to a Poisson process, and their bandwidth demands are distributed according to the following probability distribution: \( OC-1:20, OC-3:10, OC-12:10, OC-48:1 \) and \( OC-192:1 \). Connection requests are uniformly distributed among all pairs of nodes. The holding time follows a negative exponential distribution with mean of one unit.

The energy consumption of operations are defined as following: \( P_{AM} = 0.07, P_{RX} = 0.5, P_{TX} = 10, P_{OE} = 1, P_{EO} = 1.3, P_{OS} = 9.2 \) and \( P_{ES} = 18.4 \) for a wavelength capacity of \( OC-192 \) [5]. All these values are dimensionless. The overhead is defined as the ratio of the component of energy consumption independent of the traffic over the dependent component \( P_{oc} \), where \( P_T \) is the energy consumed by full-wavelength traffic, not by actually carried traffic [5] and it was set to 0.2. \( k \) was set to 10. The value of all parameters in the energy consumption equation (Eq. 1) are normalized by the capacity of one wavelength, in a way that the total consumption of the network can be computed by considering the traffic load on the lightpaths. The network load is given in Erlangs defined as the call arrival rate \( \times \) call holding time \( \times \) the calls bandwidth request normalized to the capacity of an \( OC-192 \) carrier.

The metrics used to evaluate the algorithms are the energy consumption per bandwidth, the bandwidth blocking ratio (BBR), the mean number of lightpaths used by provisioned connection and the Jains index of fairness [15] applied to the BBR per pair of node. The energy consumption per bandwidth (ECB) corresponds to the ratio of the total energy consumed by the network by the amount of bandwidth accepted. The bandwidth blocking ratio, i.e., the percentage of the amount of blocked traffic in relation to the total bandwidth requested during each simulation. Jains index of fairness is given by:

\[
f(x_1, x_2, \ldots, x_n) = \frac{\sum_{i=1}^{n} x_i^2}{n \sum_{i=1}^{n} x_i^2}
\]

Fig. 3 shows the energy consumption per bandwidth as a function of the network load. Under loads lower than 145 Erlangs, all algorithms consume the same amount of energy, which happens since most of the solutions involve single lightpaths. The EBM consumes the lowest amount of energy under network loads greater than 170 Erlang. As network load increases, singlepath algorithm becomes less efficient than the other two algorithms since by using already established lightpaths is possible to admit a higher number of request. Comparing the two multipath algorithms (Fig. 3), it is possible to verify that the bandwidth requirement of the EBM algorithm leads to considerable energy saving since by using lightpaths with large residual bandwidth, the number of lightpaths needed to provide the requested bandwidth is smaller than that required by the EM algorithm. A lower number of lightpaths implies on a lower number of transmission operations and, as a consequence, the total energy consumption decreases.

Fig. 4 shows the bandwidth blocking ratio (BBR) as a function of the network load. The EM algorithm generated BBR values lower than those given by the singlepath algorithm, since multipath routing allows flexible accommodation of the bandwidth demand. Under loads lower than 220 Erlangs, the EBM produces a higher number of accepted connections than does the EM algorithm since the set of \( k \) lightpaths selected by EM does not necessarily have residual bandwidth at least equal to the bandwidth demanded and therefore a higher number of connections in rejected.

Fig. 5 shows the mean number of lightpaths used by provisioned connection as a function of the network load. The employment of multiple paths for connection provisioning starts around 100 Erlangs, when the singlepath algorithm starts blocking requests. The number of paths used tend to stabilize after 130 Erlangs and after that the EM algorithm uses 50% more paths than does the EBM algorithm.

Fig. 6 shows the Jain fairness index resulted from the employment of the three algorithms as a function of network load. A fair algorithm must be able to provide similar values of BBR for all source-destination pairs. Under loads lower than 175, all algorithms generated low values of the fairness index due to the higher number of source-destination pairs with BBR null. As the load increases, the EBM algorithm produced the highest index values as a result of the lowest BBR produced.
The present paper introduced two energy-aware multipath grooming algorithms. Both algorithms save energy when compared to their singlepath counterpart algorithms, showcasing that the employment of energy-aware multipath approach is promising for dynamic traffic grooming in WDM networks. Furthermore, the minimum bandwidth requirement of the EBM algorithm leads to solutions which reduce the energy consumption and increase the number of accepted connections when compared to the EM algorithm since it typically employs a lower number of lightpaths for connection provisioning. The fairness produced by the EBM algorithm also outperforms the fairness of the other two algorithms.

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