Energy-efficient Connection Provisioning in WDM Optical Networks

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Abstract: A novel energy-efficient dynamic provisioning scheme is proposed by using an intelligent load control mechanism and an auxiliary graph model. Significant reduction in total energy consumption is achieved without a noticeable increase in the blocking probability.

OCIS codes: (060.1155) All-optical networks, (060.4251)Networks, assignment and routing algorithms

1. Introduction

In today's internet dominated world, bandwidth requests are continuously increasing which leads to an expansion in the carbon footprint of the network. The internet's energy consumption has already become 1-2 % of the total energy consumption in broadband-enabled countries [1]. In recent years there has been significant amount of research conducted on greening the internet [2]. Most of the effort is focused on the static design problem and to reduce the energy consumption of electronic switching and IP routing in the IP over WDM works. Energy-efficient connection provisioning in a dynamic traffic scenario is an open problem which has not been addressed yet.

The main idea behind the energy-efficient network design approaches is switching-off as many resources as possible in order to reduce the idle power which is consumed by the network devices independent of the traffic carried by those devices [2]. Energy-efficient strategies tend to pack the routings by minimizing the operating resources and may cause an increase in the load of specific links in the network and may form bottlenecks which, in turn, in a dynamic scenario, can lead to a rise in the blocking probability. In [2] the authors propose an energy-efficient network design solution by addressing this problem. However, in a dynamic scenario, new adaptive mechanisms need to be developed to control blocking probability without increasing the operational cost. In order to cope with this trade-off in this study, a load threshold is used before choosing the energy-efficient routes for the dynamic lightpath requests.

An important problem that needs to be addressed in a dynamic traffic scenario is the delay, the time needed to switch-on a fiber link, e.g., optical amplifiers in the physical layer. In this study, amplifiers and switching nodes are assumed to be able to operate at a hibernate mode other then completely turned-off when they are not used. The warming up delay is assumed to be negligible in the hibernate mode.

For the energy-aware routing of lightpaths, an adaptive auxiliary graph model of optical WDM networks is proposed which represents the energy consumption of each operation in the WDM layer. However energy-aware link weights are used only when the load is below a threshold value. Highly loaded links in the auxiliary graph is assigned load-aware weights instead of energy-aware weights by controlling the load during the link assignment phase.

A different auxiliary graph model is used in [3] for an energy-efficient design in backbone networks. In [3], the main objective is to decrease the energy consumption of electrical switching and electrical/optical (E/O) and (O/E) conversions during the add-drop process of a lightpath. Therefore it focuses on minimizing the lightpath hops in a traffic grooming scenario. Apart from the previous studies, this paper proposes an energy-aware connection provisioning scheme with dynamic traffic arrivals with the aim of minimizing the energy consumption of lightpaths in the optical WDM layer by introducing a load-aware and an energy-aware lightpath routing mechanism.

2. Energy-Aware Connection Provisioning Problem

The problem formulation of energy-aware connection provisioning (EACP) which minimizes the energy consumption in optical WDM networks can be seen in Algorithm 1. Connection requests are generated dynamically from each node. In Step 1, link weights are updated as described in the following subsection. If the algorithm cannot find an available path for request *R*, then the request is rejected (blocked) (See Algorithm 1.)

Input

1) The physical topology of a network, represented by a graph with a set of links and nodes P(N,E); number of wavelengths available on each link (W_{xy}) with a maximum wavelength number represented by W;
2) The load of each link, represented by $L_{xy}=(W-W_{xy})/W$
3) An auxiliary graph G(N, E) where adaptive link weights are assigned according to either energy-cost or link load.
4) A connection request R={s, d, t_a, t_h}, between source-destination pair (s,d) with an arrival time (t_a),and holding time (t_h).

5) Load threshold value *T*.

Output A lightpath connection *i* (P_i) is provisioned or the connection request is blocked/rejected.

Algorithm 1. EACP (Energy-aware Connection Provisioning)

1. Update the link weights in *G(N, E)*
   If $L_{xy}>T$ **Then** $C_{xy}=M.\ L_{xy}$
   Else $C_{xy}= E_{xy}$
2. Compute the minimum cost path in *G(N,E)*.
   If no path exists **BLOCK** and **EXIT**.
   Else if path is found, **set up** the lightpath and **EXIT**.

3. Adaptive Link Weight Assignments in the Auxiliary Graph with Energy Costs

In order to find the routes of the lightpaths, link weights are assigned in an adaptive manner considering the load together with the energy consumption of the link. If the load is greater or equal to a threshold (*T*) value then the cost of the link is assigned a big number (*M*) times the load (L_{xy}) of link (*x,y*) as shown in the Step 1 in Algorithm 1. Therefore highly loaded links are not chosen unless there are no more available links in the network. If the load is lower than *T* then the algorithm operates in the energy-efficiency mode where energy costs are assigned as link weights as shown in the following equation.

$$\mathrm{E}_{xy}=\begin{cases}\infty; & (i)\ \text{if } \mathrm{W}_{xy}=0\\ E_n+a_{xy}+E_s; & (ii)\ \text{if } \mathrm{l}_{xy}=0\ \wedge \mathrm{n}_x=0\\ a_{xy}+E_s; & (iii)\ \text{if } \mathrm{l}_{xy}=0\wedge \mathrm{n}_x=1\\ E_s; & (iv)\ \text{if } \mathrm{l}_{xy}=1\end{cases}$$

In the above formulation E_{xy} denotes the energy-cost weight of link (*x,y*), where E_n stands for electronic control power consumption at each node *n*, E_n denotes the total power consumption of 3D MEMS switching per wavelength and w converters. Power consumed by in-line amplifiers is calculated by the formula $a_{xy} = E_aA_{xy}$ where $A_{xy} = d_{xy}/80km+2$ assuming an optical amplifier is needed for every 80 km of reach. Transceiver energy consumption is not covered in the weight assignment since it is dependent on the number of connection requests and does not affect the routing. Case (*i*) (infinite cost) corresponds to the case of insufficient resources on a link to accommodate the path where W_{xy} stands for the number of free wavelengths in the link. Case (*ii*) corresponds to the case where link (*x,y*) and node *x* has not been utilized before by any of the lightpaths. l_{xy} and n_x are equal to 0 if link (*x,y*) and node *x* is idle, respectively. Case (*iii*) gives the energy cost of the link where amplifiers need to be switched on but the node is already in use by another path. In *Case (iv)* both link *(x, y)* and node *x* are already on so additional energy consumption by adding this candidate link will be only the switching energy.

4. Power model

In this study we consider the power model only in the optical WDM layer as the total power consumption in the network since we focus on reducing the power consumption of dynamic lightpath routing in the optical WDM layer. Other energy parameters such as cooling power, electronic conversion and switching power are not considered. In order to calculate the total energy consumption (POW) in a network at any random instant we need to know the current resource utilization: Number of fiber links and optical switching nodes which are under utilization; total number of physical wavelength links (p_{xy}) that are in use, and total number of provisioned lightpaths, λ_{sd}, operating in the network. As a result, power model can be formulated as follows where the first term corresponds to the energy consumption of amplifiers, the second term stands for the nodes' idle power, the third term is energy consumption of optical switching and the last term is for transponders.

$$POW=\sum_{\forall(x,y)\in E} a_{xy}\mathrm{l}_{xy}+\sum_{\forall i\in E} E_i\mathrm{n}_i+\sum_{\forall(x,y)\in E} E_s\mathrm{p}_{xy}+\sum_{\forall(s,d)\in R}(E_t+E_r)\lambda_{sd}$$

5. Illustrative Numerical Examples

For the performance evaluation of the algorithm, we simulated a dynamic network environment. Connection arrivals follow a Poisson process with exponentially-distributed holding time. Average holding time is normalized to unity. The network topology used in this study is a US mesh network which has 24 nodes and 43 bidirectional links [3] with link distances ranging from 250 to 2600 km. Each fiber link is assumed to have 16 bidirectional wavelength channels. Connection requests are symmetric and uniformly distributed among all node pairs. Each connection request corresponds to one lightpath operating at 10Gbps.

Power consumption parameters are set according to [4] as follows: Electronic control power consumption at each node is $E_n = 150W$. Transceiver's power consumption $E_t+E_r = 5.9W$. Optical wavelength converters and 3D MEMS switching per wavelength consumes a total $E_s = 1.757W$ of power. Power consumed by in-line amplifiers is calculated by the formula $a_{xy} = E_a A_{xy}$ where $E_a = 9W$ and $A_{xy} = d_{xy}/80km+2$.

For the performance analysis, EACP is compared with an energy unaware connection provisioning (EUCP) approach where all the lightpaths are provisioned by shortest path with load balancing threshold. In all the experiments load threshold T is equal to 0.6 and each simulation has run for 10^6 number of connections.

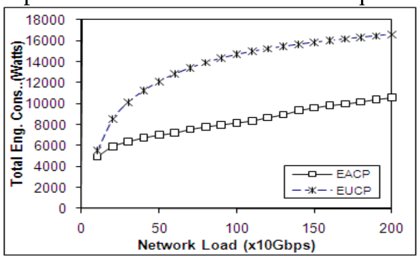

Fig. 1. Total eng.cons. vs. network load.

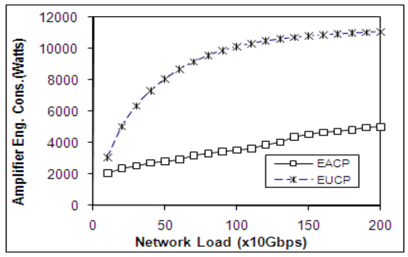

Fig. 2. Amplifier eng. cons. vs. network load

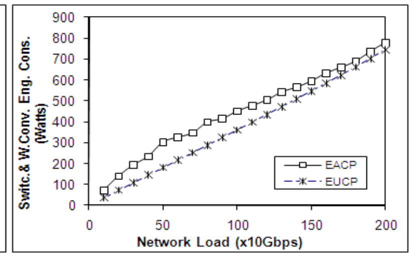

Fig. 3. Switching and w. conv. eng. cons.

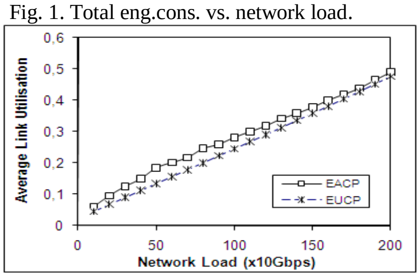

Fig. 4. Avg. link utilization vs. network load.

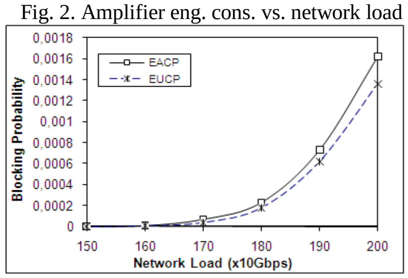

Fig. 5. Blocking probability vs. network load.

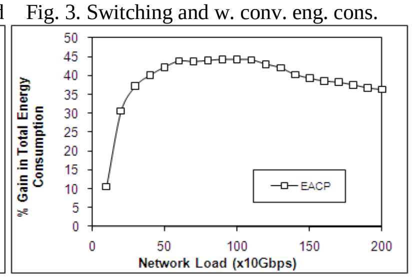

Fig. 6. Percentage gain in total eng. cons.

Fig. 1 shows that EACP saves from 37% up to 43% of total energy consumption compared to EUCP when the network load changes from 50 (x10Gbps) to 200 (x10Gbps). The saving is bigger in the low loads because it is possible to pack more the routings of lightpaths and utilize less number of physical links without creating bottleneck links. When the load increases, EACP link weight assignment in the auxiliary graph changes from energy-aware costs to the load-aware costs for the increasing number of the links. Therefore as the load increases EACP tends to behave closer to EUCP.

The constituents of the total energy consumption such as amplifier energy usage and transceiver+wavelength converter energy usage in Watts, are shown in Fig. 2 and Fig. 3, respectively. It is intuitive that EUCP consumes less energy in terms of switching as shown in Fig. 3. since it uses shortest paths and therefore utilizes a lower number of wavelength links. However, EACP achieves a significant decrease in amplifier energy consumption and compared to the optical switching power consumption, amplifiers consume a lot more energy when they are switched on. Therefore switching-off the amplifier power is prioritized more than taking longer paths in wavelengths while calculating the minimum energy path in EACP. Since EACP takes longer paths the average link utilization is slightly bigger in EACP as shown in Fig. 4.

From Fig. 5 we can see that blocking probability (BP) is slightly lower in EUCP than in EACP because EACP packs the lightpath routes in order to decrease the idle power consumption of the links. However by exploiting the load threshold and adaptively assigning the link weights in the auxiliary graph EACP considers load balancing when it comes to the links where the loads are higher than the threshold value. As a result the overall gain in energy consumption by EACP is shown in Fig. 6 and it is achieved without a significant increase in BP thanks to the adaptive auxiliary graph method.

6. Conclusion

By exploiting the auxiliary graph, the EACP achieves an up to 43 % decrease in total network energy consumption. Essentially, because the auxiliary graph link weights are assigned in an adaptive manner and EACP is load sensitive, it decreases the energy consumption without creating bottleneck links or increasing the blocking probability of the network. As a future work, (1) the performance of the algorithm will be analyzed by applying different traffic distributions covering the daily fluctuations; (2) the auxiliary graph model will be extended to cover also the energy parameters of an IP router in a dynamic scenario.

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