Energy-Efficient Lightpath Provisioning in a Static WDM Network with Dedicated Path Protection

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ABSTRACT

The interest in the energy consumption of communication networks has risen in the recent years. In an effort to tackle this problem, several approaches have been presented to reduce the power consumed by the entire network infrastructure, including optical transport. Most of the solutions studied and proposed in the literature, however, pay little or no attention to the power consumed to ensure the resiliency of the overall network.

In wavelength division multiplexing (WDM) networks resilient to single failures, an innovative strategy that can be adopted to reduce power consumption entails setting to sleep mode the optical devices supporting solely protection lightpaths. To take full advantage of this strategy, it is important to optimally route the lightpaths so that the number of devices supporting exclusively protection lightpaths is maximized. An optimal solution for this provisioning problem was previously presented, but features a limited scalability with the network size.

This paper first proposes a scalable and efficient heuristic that chooses the route of the working and protection lightpaths with the aim to maximize the power saving. The performance of the heuristic is compared with the optimal solution and a sensitivity analysis of the drained power is carried out by considering a variety of networking scenarios. Up to 20% of the network links can be set to sleep leading to significant power saving, especially at low load and when the power consumption in sleep mode is negligible.

Keywords: Green networks, energy-aware, power efficiency, dedicated path protection, static provisioning, survivable WDM networks.

1. INTRODUCTION

Energy-efficiency of wavelength division multiplexing (WDM) networks is becoming of paramount importance for reducing the operational expenditure as well as green-house gas emissions [1][2]. To achieve such a goal, energy-efficient provisioning of resources is required. Energy-efficient strategies for static [3][4] and dynamic [5][6] provisioning have been proposed. Such strategies usually optimize the energy drained by the resources used to provision the traffic, i.e., the working lightpaths.

When resilience to failures needs to be ensured, the network is equipped with additional resources for protection purposes (protection resources). Typically the protection resources are kept active even under normal conditions (i.e., absence of failures). In [7][8], the authors propose to improve the energy-efficiency of WDM networks resilient to single node/link failures not only through proper provisioning of resources for the working and the protection lightpaths, but also through an innovative way of reducing the power consumed by the protection resources. The solution is based on the intuition that if the protection resources are unused until a failure occurs, they can be set to *sleep mode*. Sleep mode represents a low-power, inactive state from which devices can be suddenly waken-up upon the occurrence of a triggering event, e.g., a failure detection. Although not yet available in most network devices, the support of a sleep mode option is currently advocated by standardization bodies and governmental programs [9].

This paper proposes an efficient and scalable heuristic algorithm for static, energy-efficient lightpath provisioning in WDM networks with dedicated 1:1 path protection [10]. Such an algorithm can encompass the scalability limitation experienced by the optimal solution proposed in [8], based on an Integer Linear Programming (ILP) formulation. This permits a more comprehensive assessment of the achievable energy savings under a variety of power consumption scenarios.

2. BENEFITS OF SLEEP MODE SUPPORT

Consider a WDM network where each node is equipped with optical cross-connects and optical wavelength converters. Assume that the optical devices on the links and at the nodes can be set to three different modes of operation [9]: *off*, *sleep*, and *active*. Full (working) functionalities are available in active mode. Null, or close to null functionalities are available in sleep and off modes with the difference that sleep mode permits a prompt transition to active mode. When sleeping, devices may consume a small amount of power to ensure that they can

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be promptly switched to active mode at any time. When active, a device drains an amount of power dependent on its specific functionalities. The overall power drained by the WDM network is, thus, given by the power consumed by the active and the sleeping devices. Given a set of lightpath requests to be provisioned, the static provisioning problem for minimum power with sleep-mode support (MP-S) can be formulated as follows: (*i*) find a route for the working and protection lightpaths (along link-disjoint routes) and (*ii*) select the modes of operation of links and nodes, with the objective to minimize the overall network power consumption. Sleep mode of operation can be applied to the network resources assigned for protection exclusively. It means that if a link or node is supporting either working or both working and protection resources it needs to be active. Therefore, to minimize the network power consumption, the network resources supporting both working and mixed (working and protection) lightpaths should to be minimized.

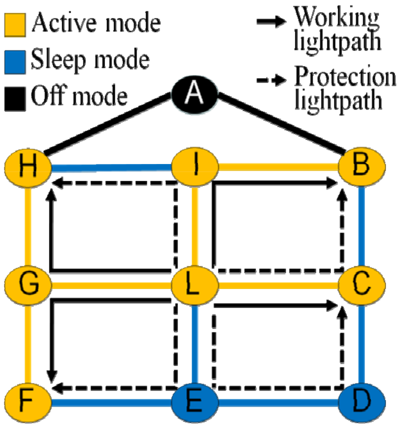

Figure 1. Example of protection resources in sleep mode.

Figure 1 shows an example, where four working lightpaths with their corresponding (link-disjoint) protection lightpaths are routed. Devices in links (L,G), (G,H), (G,F), and (I,B) need to be active as they support only working lightpaths. Also, devices in links (L,I) and (L,C) need to be active as they support both working and protection lightpaths. To save power, devices in links (A,H) and (A,B) can be turned off. Also, devices in links (L,E), (E,F), (E,D), (D,C), (C,B), and (I,H) can be set to sleep mode, as they support only protection lightpaths. Similar considerations can be derived for the devices at the nodes. Devices at node A can be turned off, devices at nodes D and E can be in sleep mode, while devices at all other nodes must remain active. Notice that routing the working lightpath from node L to node B using links (L,C) and (C,B) and the protection lightpath on (L,I) and (I,B) would enable links (L,I) and (I,B) and node I to be set to sleep mode.

As mentioned above, to minimize the overall power consumption, it is necessary to optimally route the lightpaths to have the minimum number of devices supporting working lightpaths. This in turn maximizes the number of devices that exclusively support protection lightpaths, i.e., which can be set to sleep mode. The problem and the proposed heuristic algorithm are discussed next.

3. HEURISTIC FOR STATIC PROVISIONING AT MINIMUM POWER WITH SLEEP MODE SUPPORT (MP-S)

Given the graph representing the WDM network $G(V,E)$ and the set of lightpath requests that need to be provisioned (T), the provisioning at minimum power with sleep mode support (MP-S) aims at finding the routing for the working and protection lightpaths such that the overall power consumption of the network is minimized. It is assumed that links and switching nodes drain, in active mode, an amount of power depending on their functionalities, and, in sleep mode, only a small fraction of this power. Sleep mode is enabled at the nodes and links that support exclusively protection lightpaths.

MP-S provisioning can be achieved using the heuristic described in Fig. 2. For each lightpath request belonging to set T, two shortest link-disjoint routes (in terms of geographical distance) are found using the Suurballe algorithm [11] (lines 5-8 in Fig. 2). The results are saved in set P (line 7). This initial routing is necessary to estimate the power drained by the WDM network. The routing of lightpaths is then refined (lines 11-16) by using the Suurballe algorithm on an auxiliary graph $G_p(V,E)$, starting from the lightpaths consuming the least estimated power.

Graph $G_p(V,E)$ is the same as $G(V,E)$ in terms of number of nodes, links and connectivity. The only difference is in how the weights of links and nodes are computed. They are equal to the incremental power required to establish an additional lightpath. In other words the weights used in $G_p(V,E)$ reflect the amount of power required to activate links and nodes that were either sleeping or off (disconnected from the network).

Initially, it is assumed that all the network elements are in off-mode (line 10). Once the routing of a lightpath request has been refined (line 13), the working lightpath is assigned to the least power-consuming path (line 14) and $G_p(V,E)$ is updated (line 15), i.e., the weights of the links of working lightpaths are set to null in $G_p(V,E)$ and the links of protection lightpaths are assigned a weight equal to the node and link power consumption. This is mainly due to discourage as much as possible the use of links with protection resources only.

MP-S Provisioning Heuristic

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1:  $G(V,E)$: network graph, link weight = geographical distance
2:  $G_p(V,E)$: auxiliary graph, link weight = power consumption
3:  $P$: candidate path matrix
4:  $T$: lightpath requests to be provisioned
5:  for every $i$ in $T$ do
6:      Run Suurballe algorithm on $G(V,E)$
7:      Save paths in $P(i)$
8:  end for
9:  Sort $T(i)$ for increasing power consumption along $P(i)$
10: Initial assignment of link weights in $G_p(V,E)$
11: while $T$ != empty set do
12:     Select first lightpath $i$ in $T$
13:     Run Suurballe algorithm on $G_p(V,E)$
14:     Set the path at minimum power consumption as working
15:     Update $G_p(V,E)$ and remove $i$ from $T$
16: end while
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Figure 2. Pseudo-code of the MP-S algorithm.

4. SENSITIVITY EVALUATION OF THE POWER SAVINGS

The power consumption of the proposed MP-S static provisioning heuristic is evaluated for the European core network with 14 nodes and 20 bidirectional links [12].

It is assumed that all links have the same length and that the number of wavelengths available on each link is sufficient to support the generated traffic (i.e., no wavelength blocking in the network). MP-S is compared to a static provisioning strategy at minimum power consumption (MP) without sleep mode support. The MP heuristics is identical to the MP-S heuristic except for the weights used in graph $G_p(V,E)$ and their updating procedure. In the MP heuristics the sleep mode option is not supported, thus the weights of links and nodes already in use are set to null in $G_p(V,E)$, regardless of whether they are used to provision a working or protection lightpath.

The set of lightpath requests T is generated by uniformly selecting the source and destination nodes, until a confidence interval is 4% or less is reached with a confidence level of 95%. Unless otherwise mentioned, the power drained by each node is [13]: 150 W for electronic control (i.e., idle power), 5.9 W for each transmitter and receiver required by working lightpaths, and 1.757 W for wavelength converting and optically switching each bypassing lightpath. Also, it is assumed that for amplification each link drain 30 W, independently of the number and type of lightpaths supported.

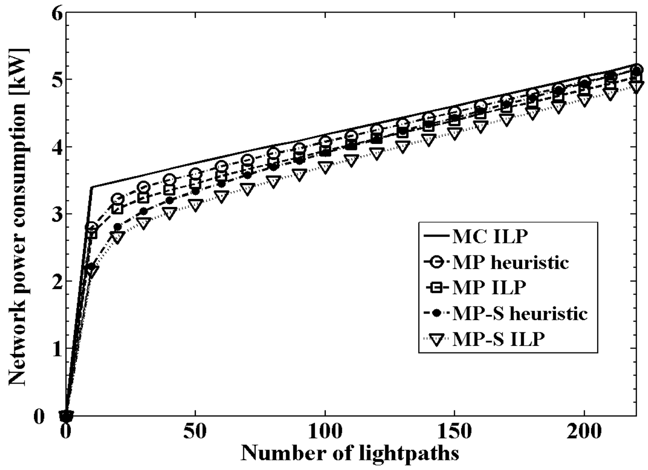

Figure 3. Network power consumption computed by ILP solver and the heuristic vs. number of lightpath requests.

In Figure 3, the heuristic performance is compared with the optimal solutions found by the ILP formulation in [8] using the CPLEX solver. The figure shows the network power consumption of MP-S and MP versus the number of lightpath requests. For benchmarking purposes, a third static provisioning solution is also presented, namely Minimum Cost (MC) [8]. The objective of MC is to minimize the number of wavelengths to be provisioned. It is shown that the heuristics proposed for MP-S and MP are able to well approximate the optimal solution (i.e., average error is below 6%) and are effective with respect to the network static provisioning solution at minimum cost. At low loads, the MP-S heuristic saves up to 20% of power with respect to the MP heuristic and up to 35% with respect to the MC strategy. At higher load, the power saving due to the energy-efficient routing (i.e., the gain of MP over MC) and due to the support of sleep mode (i.e., the gain of MP-S over MP) is reduced.

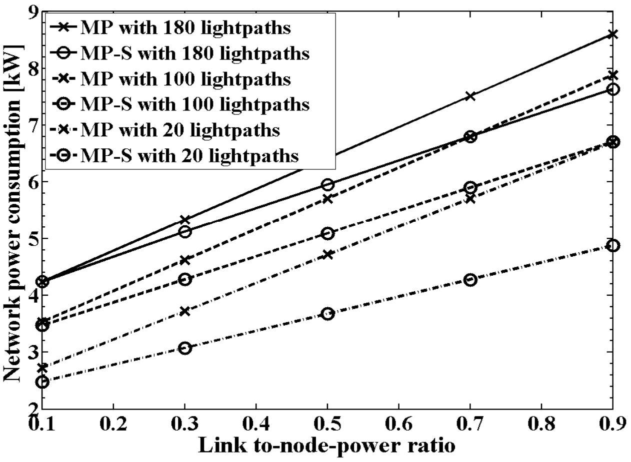

Figure 4. Network power consumption computed by the heuristic vs. link-to-node power ratio.

The sensitivity of the MP-S energy-efficiency is evaluated in Figures 4-6. In Figure 4, the link power consumption has been varied from 10% to 90% of the node power consumption, which is kept fixed. The figure shows that MP-S has the potential to significantly save power when the link consumes an amount of power close to the power consumed by the nodes, and when the number of lightpath requests is relatively low. Such savings are more significant when links in sleep mode are consuming a negligible amount of power with respect to the active links (i.e., for low ratio of sleep-to-active link power), as shown in Fig. 5.

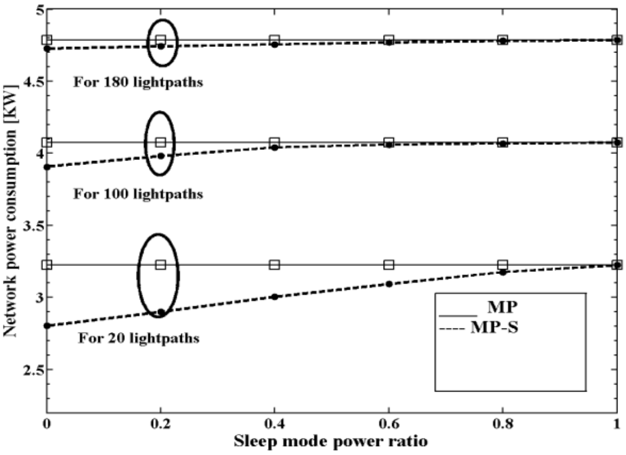

Figure 5. Network power consumption vs. sleep mode power ratio.

Notice that when the sleep-to-active link power ratio is 1, MP-S and MP coincide, since in this case links in sleep mode consume the same amount of power as the active links. The average number of links in sleep mode is displayed in Fig. 6 for different number of lightpath requests. Up to 16 links, equivalent to 20% of the network links, can be designated to support only protection lightpaths and thus can be set to sleep mode.

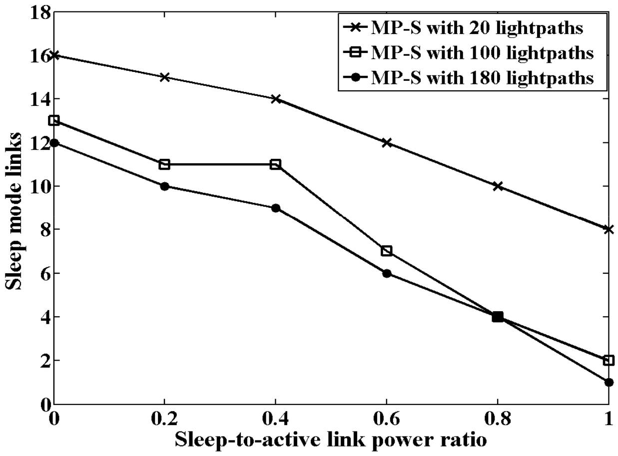

Figure 6. Number of sleeping links vs. sleep-to-active link power ratio.

5. CONCLUSIONS

In this paper a heuristic for an energy-efficient provisioning in a static and survivable WDM network is presented. The algorithm is able to assign some links and nodes to support only protection lightpaths. By setting the devices on such links and nodes to sleep mode, significant power savings can be achieved at low loads. The benefit is higher when the power consumption in sleep mode is negligible and when the link power consumption is in the order of (or greater than) the node power consumption.

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