Power-Aware Routing and Wavelength Assignment in Optical Networks *

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Abstract *We introduce the Power-Aware RWA problem, whose goal is to accommodate lightpaths in wavelength routing networks minimizing the power consumption. Formulation, algorithms, and results are presented, showing that significant power savings are possible.*

Introduction

Wavelength Routing (WR) networks offer the flexibility of designing a “logical topology”, comprising lightpath requests, over a physical topology, comprising OXCs and links with many fibers each. The Routing and Wavelength Assignment (RWA) problem is well known in the literature [1]. Its goal is to assign a route and a suitable wavelength in the physical topology for each lightpath of the logical topology. Traditionally, the goal of the RWA problem is to minimize the load (e.g., number of wavelengths) on available resources, in order to maximize the probability of accommodating possible new lightpath requests. However, this leads in general to a waste in the power required to keep up and running both OXCs and optical amplifiers along fiber links. Given the large number of these devices (thousands) and their power footprint (up to tens of kW), we propose to target the minimization of power consumption when solving the RWA problem, by making maximum usage of powered-on devices, e.g., by reusing the same fiber along the same path as much as possible, in contrast to spreading lightpaths on available fibers and paths. We name this problem *Power-Aware RWA* (PA-RWA) problem. In this paper, we give a formulation of the problem, propose heuristics to solve it, and present simulation results showing that a large amount of power can be saved in WR networks, reducing up to a factor of 5 the energy (and the cost) needed to operate a WR network.

Problem Formulation

The PA-RWA problem can be defined using an integer linear programming (ILP) formulation. Let Λ_{sd} denote the number of lightpath requests from source s to destination d, and λ_{sdw} the number of lightpaths from s to d on wavelength w: $\Lambda_{sd} = \sum_w \lambda_{sdw}$. Let $f_{ijk}^{sdw} \in \{0,1\}$ denote the number of lightpaths from s to d on fiber k of link (i,j) using wavelength w, and $f_{ij}^{sdw} = \sum_k f_{ijk}^{sdw}$. On link (i,j), let K_{ij} be the number of fibers, and F_{ijk} the number of wavelengths available on fiber k. Let a_{ijk} be the number of amplifiers on fiber k of link (i,j), and $x_{ijk} \in \{0,1\}$ be binary variables equal to 1 if fiber k on link (i,j) is used to route a lightpath. Similarly, let $y_i \in \{0,1\}$ be binary variables equal to 1 if OXC i is used. Finally, let P_A and P_O be the power consumptions of one amplifier and one OXC, respectively. We do not consider the possibility of powering off individual transceivers or subsystems in OXCs. The notation above leads to the following ILP formulation of the PA-RWA problem:

$$\min P_{tot};\ P_{tot} = P_A \sum_{i,j,k} a_{ijk} x_{ijk} + P_O \sum_i y_i \quad (1)$$

$$\text{s.t.} \quad \sum_{s,d} f_{ijk}^{sdw} \le 1 \quad \forall w,i,j,k \quad (2)$$

$$\sum_{s,d,w} f_{ijk}^{sdw} \le M x_{ijk} \quad \forall i,j,k \quad (3)$$

$$\sum_{j,k} x_{ijk} + \sum_{j,k} x_{jik} \le M' y_i \quad \forall i \quad (4)$$

$$\sum_k f_{ijk}^{sdw} = f_{ij}^{sdw} \quad \forall s,d,w,i,j \quad (5)$$

$$\sum_i \left(f_{ij}^{sdw} - f_{ji}^{sdw} \right) = \begin{cases} -\lambda_{sdw}, & j = s \\ \lambda_{sdw}, & j = d \ \forall s,d,w,j \\ 0, & j \ne s,d \end{cases} \quad (6)$$

$$\sum_{s,d,w} f_{ijk}^{sdw} \le F_{ijk}\ \forall i,j,k;\ \sum_k x_{ijk} \le K_{ij}\ \forall i,j \quad (7)$$

Eq. 1 is the utility function. Eq. 2 constraints a wavelength on a fiber to be assigned to at most one lightpath; Eq. 3 imposes that a fiber is used if at least one wavelength is assigned (M, and later M', are sufficient large constants); Eq. 4 state that OXC i has to be powered on if any of its fibers is used; Eq. 5 counts the number of fibers; Eq. 6 are the classical routing constraints, assuming no wavelength conversion functionality; finally Eqs. 7 limit the number of wavelengths on each fiber, and the number of fibers in each link.

Algorithms

Following a well-established approach, the problem is divided in two parts: routing and fiber&wavelength assignment. Considering the routing problem, we implemented three heuristics: Least-Cost Path (LCP) [1], Most-Used Path (MUP) and Ordered-Lightpath Most-Used Path (OLMUP). All algorithms start with a network where $y_i = 0$ and $x_{ijk} = 0\ \forall i,j,k$; the initial cost for each link is $c_{ij} = a_{ij} P_A + P_O$ (assuming for simplicity that $a_{ijk} = a_{ij}\ \forall k$). The main steps of each algorithm are described below.

LCP: for each request, compute the shortest path P using c_{ij} as *static routing costs*.

MUP: for each request, compute the shortest path *updating the routing costs* of links used to route the current lightpath request. Using a pseudo-code notation, for each lightpath λ_{sd}

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compute the shortest path P_{sd} using costs c_{ij}

$c_{ij} = 0 \; \forall (i,j) \in P_{sd}$

OLMUP: at each iteration, select the lightpath to be routed as the one that minimizes the incremental cost (Lightpath Selection –LS– phase). Then route it using the *MUP* algorithm (Routing Update –RU– phase). During LS, find the lightpath that has the *minimum incremental cost*: for each lightpath λ_{sd} not yet assigned

compute the shortest path P_{sd} using costs c_{ij}

compute the incremental cost $C_P = \sum_{ij \in P_{sd}} c_{ij}$

if $C_P < C_{min}$ then $C_{min} = C_P$; $s' = s$; $d' = d$;

$$P' = P_{sd};\ \lambda' = \lambda sd$$

During RU, route λ' on P' using the *MUP* algorithm.

Considering the fiber&wavelength assignment problem, we use in all cases a simple First-Fit strategy (FF) which has been proved to be one of the most effective algorithms [1]: for each lightpath, considering first powered-on fibers, wavelengths are sequentially scanned for availability on the whole path. If no wavelength is found, a new fiber is powered on in each link. In case no assignment is possible, a new path is computed, forbidding links in the previously chosen path. Finally, for all used fibers and OXCs, set $x_{ijk} = 1$ and $y_i = 1$ and compute P_{tot} as in Eq. 1.

To compare results, we define a rough lower bound (LB) by considering that at least all OXCs which are source or destination of a lightpath request must be powered on, and that at least the cheapest fiber must be used to exit from s or to arrive to d for each lightpath.

Performance Evaluation

Several scenarios were studied in [2]. We report here results considering physical topologies which are either bidirectional rings, or generic meshes (generated considering a probability 0.5 of having a link between any two OXCs). We assume $K_{ij} = 10$ and $F_{ijk} = 128$, and $P_A = P_O = 1kW$. The number of amplifiers on each fiber a_{ijk} is instead a discrete random variable uniformly distributed in $[0, 10]$.

We first consider a set of randomly chosen lightpaths, so that there is a lightpath between any two nodes with probability 0.5. Fig. 1 reports the total power consumption required to route all lightpath requests versus the number of OXCs N in the physical topology. Results are obtained averaging over 10 independent

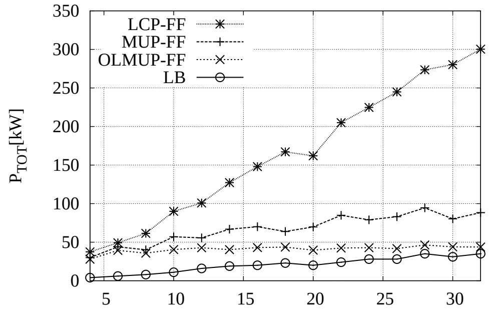

Fig. 1: Power Consumption vs number of nodes – random physical topology

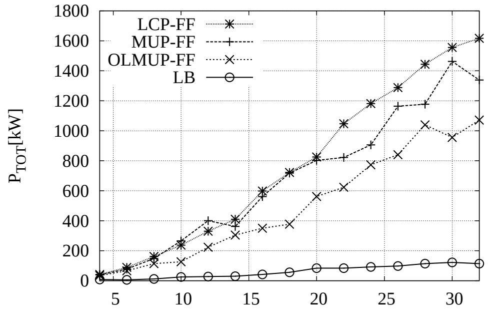

Fig. 2: Power Consumption vs number of nodes – bidirectional ring physical topology

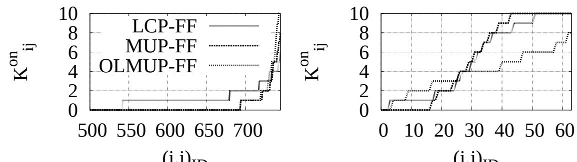

Fig. 3: Number of used fibers vs link ID – random topology on the left, and bidirectional ring on the right. $N = 32$.

runs. Using LCP-FF, which is almost power-unaware, the power consumption of the network grows as $10N$, since no spatial reuse is enforced. Considering on the contrary both the MUP-FF and OLMUP-FF heuristics, much better results are obtained, due to the power-aware routings, with the OLMUP-FF being very close to the lower bound. The energy saving can be very significant even for small networks, e.g., for $N = 24$ nodes the power consumption is approximately reduced by a factor of 5, i.e., around 200kW of saving.

Considering a bidirectional ring physical topology, Fig. 2 details P_{TOT} versus N: also in this case OLMUP-FF shows the best results. Notice that the total power consumption is much larger in this scenario, and the lower bound is not very tight. This is due to the regularity of the physical topology, in which path lengths are larger [$O(N)$ versus $O(\ln(N))$], and to less alternatives in path selection. Still power saving achieved by OLMUP-FF is larger than 400kW if $N = 24$.

Fig. 3 reports the number K_{ij}^{on} of fibers powered on for each link (omitting links where $K^{on} = 0$). It shows that LCP-FF always uses more fibers (therefore more power) than the other two heuristics which on the contrary try to reuse as much as possible already used links. This holds true for both physical topologies. In case of the bidirectional physical topology, a larger percentage of links are required as expected.

While the considered scenario, with large numbers of fibers on each link and of wavelengths per fiber compared to the number of lightpaths, eases the reduction of devices that must be powered on, our results still bring evidence to the fact that new design criteria aimed at power saving can be very effective.

References

1 H. Zang at al., “A Review of RWA Approaches for WR Networks”, *SPIE Optical Networks Mag*, 2000

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