Energy-Efficient Design of Wavelength-Routing Networks

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Abstract *We discuss the power-aware Logical Topology Design problem in wavelength routing networks, and analyze the economical impacts of power-efficiency. Results show that energy-optimized logical topologies can bring significant economical savings.*

Introduction

ICT is estimated to be responsible for a percentage from 2% to 10% of the worldwide energy consumption[1], and current trends predict that the Internet will consume 50% of the world electricity soon. A more energy-conscious telecommunication network design can therefore significantly reduce global energy consumptions and costs.

Backbone networks consume today 20% of the total energy of the Internet and their power consumption could become the dominant part of the overall Internet energy requirements in a close future[2]. Wavelength Routing (WR) networks are today a very common solution for backbone networks; they exploit WDM fiber links and optical crossconnects to provide end-to-end optical circuits called lightpaths. WR network design mainly focused on optimizing network resources minimizing capital expenditures (CAPEX). As the energy demand and its cost increase, power efficiency becomes an increasingly important parameter in network design. As an example, power consumption is one of the most important contributions to the operational expenditure (OPEX) for the incumbent Italian operator[3].

An important step in designing WR networks is to find a suitable Virtual Topology (VT): given a node-to-node traffic matrix and a physical topology, find which nodes should be connected "directly", i.e., through lightpaths, satisfying some optimality criteria. The VT design process normally goes through two phases: i) the Logical Topology Design (LTD) problem: given a node-to-node traffic matrix, find the best Logical Topology (LT) interconnecting nodes (best set of lightpaths in terms of cost, price, and/or performance) disregarding the physical topology, and ii) the Routing and Wavelength Assignment (RWA) problem: given the physical topology and a set of end-to-end lightpaths, find a route and assign a wavelength to each lightpath, so as to satisfy a given optimality criterion, possibly subject to the wavelength continuity constraint. There are two main reasons why often the two problems are faced and solved independently, thereby taking a sub-optimal approach. First, the combined solution is often unfeasible because of computational complexity. Second, the owner of the physical infrastructure and the LT designer typically belong to independent organizations: a provider of transport capacity (often a telecom operator) faces the RWA problem on the basis of a LT defined by a provider of access services to users (an ISP or an Intranet administrator), which independently solves the LTD problem.

It was previously shown that Power-Aware RWA strategies can significantly reduce power consumption, even for small-size networks[4]. Here, we focus instead on the Power-Aware-LTD (PA-LTD) problem: find the best energy-wise LT given a node-to-node traffic matrix. Differently from[5], we do not assume any particular physical topology and node architecture, but we investigate the LTD problem to find a good energy-wise balance between deployment of electronic and optical technologies. More precisely, we present a model to explore the cost trade-offs between transmitting data in the *optical* domain and switching/processing data in the *electronic* domain. Analyzing the economical impact of PA-LTD, we show that, although energy-efficient telecommunication infrastructures can initially lead to larger CAPEX, they can finally translate into lower OPEX, making power-aware WR networks sustainable and more cost effective.

Problem Formulation

We assume that each network node is equipped with a set of optical transceivers and an electronic switch, performing traffic grooming and switching. Data are transferred from node to node in the optical domain through lightpaths, and possibly switched in electronics from a lightpath to another lightpath if a multi-hop (i.e. comprising more than one lightpaths) path is chosen in the LT from the source node to the destination node. We wish to trade off, from a power consumption perspective, the amount of electronic switching/processing with the number of optical transceivers each node must be equipped with. For instance, if the power consumed by optical transceivers is negligible with respect to the power required to switch

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data in electronics, an energy-efficient solution would lead to a full mesh (FM) topology, in which electronic switching is almost completely avoided (only the transmitted and received traffic must be processed in electronic). On the contrary, if the power consumed by the optical transceivers is considerably larger than the power needed to process data in the electronic domain, a star topology minimizes the power consumption thanks to the minimum number of lightpaths. However, the most energy-efficient topology is only part of the problem. It is also important to assess the economical impact of selecting one topology with respect to another. Coming back to the previous example, a FM topology requires a number of transceivers scaling with $O\left(N^2\right)$, which implies a large CAPEX investment, whereas the number of flows each node must process in electronics scales with $O\left(N\right)$, since each node switches only its transmitted and received traffic, typically leading to a lower OPEX. A star topology requires only $O\left(N\right)$ transceivers, i.e., lower CAPEX but, since the star hub needs to process a number of flows scaling with $O\left(N^2\right)$ it might lead to higher OPEX.

We define the Power-Aware-LTD (PA-LTD) problem and the economical model that we will use to evaluate different LTs. We use i and j as node indexes (with $i,j \in N$) when referring to nodes switching traffic, and s and d (with $s,d \in N$) as source and destination nodes. The input to the PA-LTD problem is the node-to-node traffic matrix $\underline{\underline{T}} = \left[\lambda^{sd}\right]$ in bit/s. Let δ be the maximum number of transceivers a node can be equipped with, B^{SW} the maximum electronic aggregate capacity a node can process, and B^{TX} the transceiver capacity, both in bit/s. Let λ_{ij}^{sd} be the traffic transmitted by s to d flowing on link (i,j). Let $\lambda^s = \sum_d \lambda^{sd}$ be the aggregated traffic for source node s and $\lambda_{ij}^{s} = \sum_d \lambda_{ij}^{sd}$ the traffic transmitted by s on logical link (i,j). The outputs of the PA-LT problem are $\lambda_i = \sum_s \lambda^{si} + \sum_{j,s,i\neq s} \lambda_{ij}^{s} + \sum_d \lambda^{id}$, the total amount of traffic node i must process in electronic (i.e., the sum of the received, forwarded and transmitted traffic, respectively), and n_{ij}, the number of optical transceivers node i uses to transmit to node j.

For simplicity and without loss of generality, we present a Mixed Integer Linear Programming formulation considering that all node transceivers operate at the same bitrate B^{TX}. We call P^{TX} the power consumed by an optical transceiver operating at B^{TX} bit/s. We assume continuous-wave transmission: transceivers are always on and consume a fixed amount of power independently of the transmitted traffic. Let $P^{SW}\left(\lambda_i\right)$ be the power consumed by node i in processing λ_i units of traffic in the electronic domain. We assume that $P^{SW}\left(\lambda_i\right)$ is proportional to the amount of processed data[6]; thus, $P^{SW}\left(\lambda_i\right) = \lambda_i/\Delta$, where $\Delta = B^{TX}/P^{SW}\left(B^{TX}\right)$ is a constant proportionality factor measured in bit/s/Watt. In addition, let $\nu^O = \frac{P^{SW}\left(B^{TX}\right)}{P^{TX}}$ the ratio between the power used by an optical transceiver operating at B^{TX} and the power consumed by a node to process information in the electronic domain at rate B^{TX}. Thus, $P^{SW}\left(\lambda_i\right) = \frac{\lambda_i}{B^{TX}}\nu^O P^{TX}$.

The total power of a given LT is the sum of the total power for *electronic* switching $P^E = \sum_i P^{SW}\left(\lambda_i\right)$, and the total power used for *optical* transmission $P^O = P^{TX}\sum_{i,j} n_{ij}$. Thus, the objective function to be minimized for the PA-LTD is $F = P^E + P^O$, subject to the following constraints:

$$\sum_i (\lambda_{ij}^s - \lambda_{ji}^s) = \begin{cases} -\lambda^s, \; j = s, \; \forall j \\ \lambda^{sj}, \; j \neq s, \; \forall j \end{cases} \quad (1)$$

$$\sum_s \lambda_{ij}^s \leq n_{ij} B^{TX}, \; \forall (i,j) \quad (2) \qquad \sum_{j,s} \lambda_{ij}^s \leq B^{SW}, \; \forall i \quad (3)$$

$$\sum_j n_{ij} \leq \delta, \; \forall i \; ; \; \sum_i n_{ij} \leq \delta, \; \forall j \quad (4)$$

Eq. (1) represents the flow conservation constraints. Eq. (2) limits the traffic exchanged by node i and j to the bandwidth deployed between i and j, while Eq. (3) bounds the amount of traffic node i can switch to B^{SW}. Eqs. (4) limit the maximum number of transceivers per node to δ.

For the LT cost, we assume that it is dominated by the monetary cost of all transceivers only, since it is difficult to evaluate the monetary cost of processing data in electronics. We also assume that each node is equipped with the same switching engine; thus, this cost becomes a constant regardless of the LT, and can be neglected. The LT CAPEX is thus evaluated as $C = C^{TX}\sum_{i,j} n_{ij}$, where C^{TX} is the transceiver cost. We refer to Cost Aware-LTD (CA-LTD) as the above optimization problem where we set $F = C$.

We compare PA-LTD and CA-LTD both in terms of CAPEX and OPEX, evaluating their Present Value of Annuity (PVA). In finance, the annuity refers to any terminating stream of fixed monetary flows over a specified period of time. In our case, the PVA is the sum of the capital costs C and of the operational costs O. Since we consider power as the main factor contributing to the OPEX[3], the yearly OPEX is $O = PTc$, where c is the monetary cost in \$/(Wh) for a network operator and T is the number of hours in one year. Let k be the interest rate over the investment period. Thus,

$$\mathrm{PVA}\left(n\right) = C + O\sum_{l=0}^{n} \frac{1}{\left(1+k\right)^l} \quad (5)$$

is the PVA at year n.

Tab. 1: LT dependence with ν^O and C^{TX}=500$

low traffic						
ν^O	CAPEX (K$)		OPEX(K$)		$\overline{n}$	
	PA	CA	PA	CA	PA	CA
1	15	15	1	1	1.8	1.8
2	15	15	1.6	1.6	1.8	1.8
5	15	15	3.3	3.3	1.8	1.8
10	15	15	6.2	6.2	1.8	1.8
20	120	15	11.4	12	15	1.8
30	120	15	15.5	17.8	15	1.8
$high$ traffic						
ν^O	CAPEX (K$)		OPEX(K$)		$\overline{n}$	
	PA	CA	PA	CA	PA	CA
1	80	80	6.2	6.2	10	10
2	120	80	10.1	10.1	15	10
5	120	80	20.2	21.9	15	10
10	120	80	37	41.5	15	10
20	120	80	70.6	80.7	15	10
30	120	80	104.3	120	15	10

Tab. 2: BEP in years

ν^O	1	2	5	10	20	30
$C^{TX} = 500$ $						
low	-	-	-	-	-	-
$high$	-	-	32	10	4	3
$C^{TX} = 100$ $						
low	-	-	-	-	-	10
$high$	-	-	5	2	1	0.5

Results

To study the impact of both PA-LT and CA-LT optimizations on OPEX and CAPEX, we consider a small network of $N = 16$ nodes, with a uniform traffic matrix, using the AMPL+CPLEX optimization environment. Among the several considered traffic scenarios, we show results for two network loads: $\lambda^s = 0.9B^{TX}$ (low traffic) and $\lambda^s = 7.5B^{TX}$ ($high$ traffic). In our optimization runs, ν^O ranges in [1, 30]. The transceiver characteristics are: $B^{TX} = 10$ Gbit/s, $P^{TX} = 8$ Watt[6], $C^{TX} = [100, 500]$ $[7], to represent some variability in transceivers' costs. The unitary cost of electricity is set to $c = 0.2$ $/kWh[3]. Finally, in the PVA evaluation, k is assumed to be 2%, according to the expected inflation rate.

The CAPEX and the yearly OPEX for the PA-LT and the CA-LT are shown in Table 1 for the two traffic loads. The last two columns indicate the average number of lightpaths per node ($\overline{n}$). When the traffic is low, almost independently of ν^O, both the PA-LTD and the CA-LTD return networks with a low connectivity degree (in particular, the outcome is a star with $\overline{n} = (15\times1+1\times15)/16 = 1.8$). When optical transmission becomes highly convenient with respect to electronic switching ($\nu^O \geq 20$), the PA-LT becomes a full mesh ($\overline{n} = 15$), achieving a reduced yearly OPEX, which contributes to compensate for the higher CAPEX. As the traffic load increases, $\overline{n}$ increases too. Indeed, for the $high$ traffic scenario and independently of ν^O, CA-LTD optimizes the transceiver utilization, grooming traffic as much as possible, and the optimal solution becomes a partial mesh. On the contrary, since PA-LTD does not aim at maximizing transmitter utilization, PA-LTs usually show a higher $\overline{n}$ which increases with ν^O, converging to a full mesh already for $\nu^O = 2$. Table 2 reports the Break Even Point (BEP), expressed in years, i.e., the time required to recover the larger CAPEX for the PA-LT with respect to the CA-LT. A dash in the table means that PA-LTD and CA-LTD generate the same topology or that the resulting economical advantage is too small to provide a useful BEP. As the load increases, it becomes convenient to move traffic from the electronic to the optical domain for smaller values of ν^O, and the LT becomes increasingly connected. BEP's behavior depends on ν^O and C^{TX}: as ν^O increases and/or C^{TX} decreases, the BEP shortens. These behaviors are confirmed on other traffic scenarios, not reported here for space limitations.

Conclusions

We showed the benefits of power-aware approaches to the design of LTs in WR networks. Since we assumed current small-volume prices for transceivers (not considering economy of scale, nor volume discounts), economical advantages obtained by power-efficient techniques can be even more significant.

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