Optimal Design of Green Multi-layer Core Networks

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ABSTRACT

We consider the power-efficient design of an Internet Protocol (IP)-over-Wavelength Division Multiplexing (WDM) network, tackling the problem of deciding which equipment needs to be installed in both the optical and IP layer. Our model explicitly targets the minimization of cost considered as either Capital Expenditures (CapEx) or power. In contrast to the models already presented in the literature, we take into account routing constraints and consider a comprehensive set of realistic scenarios defined by a network topology, traffic, cost and power values of network devices in both layers. Results indicate that the introduction of realistic constraints and parameters still allows power-efficient networks to be designed. The total power consumption in the considered network scenarios is at most 26.5 % higher than when using previous models.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design; C.4 [**Performance of Systems**]: Design studies

Keywords

Network Design; Optical Networks

1. INTRODUCTION

Network equipment is estimated to consume 25 GW of power worldwide (2008 yearly average [17]). A major fraction of the power consumption is moving from access to backbone [14] calling for power-efficient solutions in the core. A lot of work has been performed recently on energy-efficiency in telecommunication networks [2, 3, 13, 24], and different research projects are currently targeting energy-efficient networking. Of particular note is the project TREND (Towards Real Energy-efficient Network Design) [21], the Network of Excellence funded by the European Commission within its 7th Framework Programme, which supported the work reported in this paper.

Core networks are a major contributor to the energy consumption of network equipment. Today's core segments of the network are usually implemented using two separate layers: an optical layer exploiting WDM technology and a transport layer taking care of routing at the IP level. Multi-layer networks provide flexibility in network management together with the possibility of transporting huge amount of data. Normally, a core network is composed of high-performance devices, each of them consuming tens of kilowatts [12], due to high data rates and cooling systems. Moreover, optical links covering long-haul distances require signal regeneration, and several amplifiers are needed to connect two endpoints of a single link. Therefore, part of the power consumption of a multi-layer network is due to the optical layer devices. However, multi-layer core networks are in general designed with the objective of CapEx minimization. Moreover, multi-layer networks fulfill the specific requirements of a network operator, e.g., reliability, survivability, and guaranteed Quality of Service (QoS) for users. However, several questions arise: How to design a green IP-over-WDM network from scratch? How much is this design different from a traditional one? What is the impact of introducing realistic constraints in the network design? The answer to these questions is the goal of this paper. In particular, we consider the entire network design of an IP-over-WDM network, meaning that we look not only at the IP layer deciding which routers and line cards to install and how to route the traffic over the set of IP links, but also at the realization of the IP links in the WDM layer and consider installation of fibers on the physical links. We then study the design problem considering the power as a cost, with the aim of deciding which devices to install at each layer in order to minimize the power consumption of the network.

In the literature, the topic of power-aware design of optical backbone networks has been investigated in different works [16, 18, 19]. However, all of them make simplified assumptions in the design phase. In particular, all of them assume Multi-Commodity Flow (MCF) [1], i.e., the typical transportation problem where multiple commodities (traffic demands) need to be routed over a network with limited capacity. However, MCF assumes that a traffic demand can be split over different paths. This assumption often can not be applied in a realistic telecommunication network, since many routing protocols at the IP layer are constrained to Single-Path Routing (SPR), i.e. the traffic demand between a source and a destination is entirely routed over the same IP path. Therefore, the applicability of the proposed approaches is limited in a realistic scenario. In this paper, instead, we follow a different approach: we design optical networks considering the constraints imposed by routing. Moreover, we parametrize our problem with traffic sets originating from measurements, realistic network topologies, power and CapEx values. We formulate the design model as an optimization problem with SPR constraint, explicitly targeting cost minimization being either power or CapEx. The comparison of

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SPR and Multi-Path Routing (MPR) has, to the best of our knowledge, not been studied so far in the context of the design of power-efficient IP-over-WDM networks. We verify whether the intuition that usage of MPR (corresponding to MCF) brings substantial power benefits over SPR at the network design stage. Moreover, we compare the power-minimized network with the traditional CapEx-minimized network in terms of power consumption. Finally, we perform a precise analysis of the deployed devices and their share in total network power consumption.

Results, obtained over an extensive set of realistic scenarios, indicate that the assumption of SPR and the introduction of realistic parameters still allow to design power-efficient networks. We believe that these results are beneficial for telecom operators and manufacturers, paving the way for designing future low-cost and energy-efficient networks.

The paper is organized as follows: Section 2 details the problem formulation. The description of adopted networks and cost models is reported in Section 3. Optimization results are presented and discussed in Section 4. Section 5 reviews the related work, while the challenges for green optical design are discussed in Section 6. Finally, Section 7 presents conclusions and future work.

2. PROBLEM FORMULATION

We model an IP-over-WDM network, where the WDM layer offers optical by-pass technology. Nodes in the WDM layer are equipped with Optical Cross-Connects (OXCs). Physical links between WDM nodes are realized by fibers. OXCs may connect incoming WDM channels to outgoing ones (assuming full wavelength conversion capability), or terminate them in the corresponding nodes equipped with routers in the IP layer. The IP layer is interconnected with the WDM layer by colored router line cards performing optical-electrical-optical conversion. IP routers can be equipped with several line cards. Lightpaths, which are concatenations of WDM channels on neighboring fibers, terminate in the line cards. All parallel lightpaths between two IP routers form a logical link in the IP layer. A lightpath between two particular line cards may be realized (routed) over different physical paths in the WDM layer. The IP traffic demands are routed over the logical links defined by the set of lightpaths.

In the following, we first present the model assuming SPR, followed by the model assuming splittable MCF. Both the presented formulations fall in the class of Mixed-Integer Linear Programmings (MILPs) problems, which are known to be NP-hard. However, we reduce their complexity to a high extent.

2.1 SPR Multi-Layer Problem

Building on the top of the models presented in [13, 15], let us represent the physical supply network as an undirected graph $G = (V, E)$ where V is the set of nodes where routers can be installed and E is the set of admissible physical links at which fibers can be installed. Each node $i \in V$ can be equipped with an IP router n out of the set N of IP routers. For each router $n \in N$, R^n and α^n are the maximum switching capacity and the associated cost, respectively. Let β^e be the cost of a fiber installed on physical link $e \in E$. B denotes the capacity of a fiber in terms of wavelength channels. An OXC of infinite capacity is assumed at every physical network node.

We then consider the physical routing. Let P be the set of all admissible physical routing paths in G for all node pairs $(i, j) \in V \times V, i < j$. $P_i \subset P$ is the subset of all admissible physical routing paths ending at node $i \in V$. $P_{(i,j)} \subset P$ is the subset of all admissible routing paths in G between nodes i and j for every node pair $(i, j) \in V \times V, i < j$. $P_e \subset P$ is the subset of all admissible physical routing paths traversing admissible physical link $e \in E$. Let us denote by C the module of bandwidth that can be installed on each path $p \in P$. Each module of bandwidth C on a path p incurs cost γ of line cards at the end-nodes of p, and uses one wavelength channel on every physical link of the physical routing path. δ denotes the maximum admissible utilization of bandwidth installed on each path $p \in P$. δ takes values between 0 and 100 %. Bandwidth installed on all physical paths $p \in P_{(i,j)}$ for $(i, j) \in V \times V, i < j$ form a logical link between nodes i and j. All logical links together with V constitute the logical topology.

Let d_{ij} be the undirected traffic demand value from node i to node $j, i < j$. Let total demand value d_i of a network node i be the sum of all traffic demands originating/terminating at i, i.e., $d_i = \sum_{j \in V \setminus \{i\}} (d_{ij} + d_{ji})$.

We then introduce the variables. Let f_{ij}^{ab} be binary variables taking the value 1 if traffic demand between nodes a and b uses logical link between nodes i and j, 0 otherwise. Let $y_p \in \mathbb{Z}_+$ be the number of lightpaths realized on $p \in P$. Let $z_e \in \mathbb{Z}_+$ be the number of fibers installed on physical link $e \in E$. Finally, let x_i^n be binary variables taking the value of 1 if router $n \in N$ is installed at node $i \in V$, 0 otherwise.

Given the previous notations, we formalize the MILP as (1).

$$\min \sum_{i \in V, n \in N} \alpha^n x_i^n + \gamma \sum_{p \in P} y_p + \sum_{e \in E} \beta^e z_e \tag{1a}$$

$$\sum_{j \in V \setminus \{i\}} (f_{ij}^{ab} - f_{ji}^{ab}) = \begin{cases} 0 & i \neq a, i \neq b \\ 1 & i = a \\ -1 & i = b \end{cases}, \qquad \forall (a,b) \in V \times V, \ \forall i \in V \tag{1b}$$

$$\sum_{p \in P_{(i,j)}} \delta C y_p - \sum_{a \in V} \sum_{b \in V} d_{ab} (f_{ij}^{ab} + f_{ji}^{ab}) \ \geq \ 0, \qquad \forall (i,j) \in V \times V, \tag{1c}$$

$$\sum_{n \in N} R^n x_i^n - \sum_{p \in P_i} C y_p \ \geq \ d_i, \quad \forall i \in V \tag{1d}$$

$$\sum_{n \in N} x_i^n \ \leq \ 1, \quad \forall i \in V \tag{1e}$$

$$B z_e - \sum_{p \in P_e} y_p \ \geq \ 0, \quad \forall e \in E \tag{1f}$$

Control variables: $f_{ij}^{ab}, f_{ji}^{ab}, x_i^n \in \{0,1\}, y_p, z_e \in \mathbb{Z}_+$

In particular, the objective (1a) is to minimize the total cost of the network. Constraints (1b) ensure the flow conservation constraints, and impose single-path routing of the traffic demands over the logical topology. Constraints (1c) guarantee enough bandwidth on the admissible physical routing paths to accommodate the traffic flows. Logical node capacity constraint is imposed by constraints (1d), i.e., the capacity of a node is higher or equal to the bandwidth of attached lightpaths and the demand emanating at the node. Constraints (1e) select a single configuration for each router at each node. Constraints (1f) limit the number of wavelengths used at each fiber.

2.2 MCF Multi-Layer Problem

We need to make the following changes to (1) in order to design a network with splittable flows. We introduce the set of commodities K based on point-to-point demands $d_{ij}, (i, j) \in V \times V, i < j$. The set $K \subseteq V$ corresponds to those nodes in V that are source of at least one demand. For commodity $k \in K$ and every node $i \in V$

Table 1: Cost of optical components and of line cards [9, 10, 12]

TYPE	DETAILS	CapEx [unit]	Power [W]
IP/Multiprotocol Label Switching (MPLS) Router Slot Card	40 Gbps capacity, 1 slot/1 slot	9.17	350
IP/MPLS Router Port Card	4 x 10 Gigabit Ethernet, Long Reach (1550 nm, 80 km reach), 1 slot occupied (40 Gbps)	4.20	150
WDM muxponder	10G x 4, Extended Long Haul (ELH) (1500 km)	6.05	colored interface without muxponder
Optical Line Amplifier (OLA)	ELH (80 km span)	2.77	*(i)* 110, *(ii)* 622
Dynamic Gain Equalizer (DGE)	80 channel systems	3.17	0
WDM Terminals (multiplexer/demultiplexer + booster/receiver amplifier)	80 channel, (Long Haul (LH), ELH, Ultra Long Haul (ULH))	10.83	*(i)* 240, *(ii)* 811
Dispersion Compensating Fiber (DCF)	ELH (1500 km reach) with costs related to OXCs, L^e denotes the length (in km) of physical link $e \in E$	$2 \cdot 10.42 + 0.0091 \cdot L^e$	0

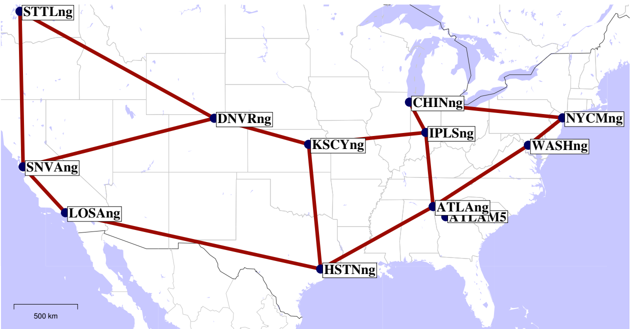


Figure 1: Physical supply topology of the Abilene network.

we define the net demand value

$$d_i^k = \begin{cases} \sum_{j \in V} d_{ij} & \text{for } i = k \\ -d_{ki} & \text{otherwise}. \end{cases} \tag{2}$$

With this definition we subsume all demands whose source is $k \in V$. It holds that

$$\sum_{i \in V} d_i^k = 0 \tag{3}$$

for all $k \in K$. Notice that the total demand value d_i of a network node i can be expressed as

$$d_i = \sum_{k \in K} |d_i^k|. \tag{4}$$

Introduction of commodities reduces the number of variables and constraints to $\mathcal{O}(|V|^3)$ and $\mathcal{O}(|V|^2)$, respectively.

In order to assure splittable flows, the flow variables must reflect the actual flow of the commodities between a given node pair. Therefore we replace the $f_{ij}^{ab}, f_{ji}^{ab} \in \{0, 1\}$ with $f_{ij}^k, f_{ji}^k \in \mathbb{R}_+$. Consequently, the constraints (1b) and (1c) need to be changed accordingly to

$$\sum_{j \in V \setminus \{i\}} (f_{ij}^k - f_{ji}^k) \; = \; d_i^k, \quad \forall i \in V, \forall k \in K \tag{5}$$

and

$$\sum_{p \in P_{(i,j)}} \delta C y_p - \sum_{k \in K} (f_{ij}^k + f_{ji}^k) \; \geq \; 0, \quad \forall (i,j) \in V \times V, \tag{6}$$

respectively.

The complete MILP of the network design problem with MCF can be found in [13] with δ equal to 1.0.

3. SCENARIO DESCRIPTION

We first detail the considered networks and the corresponding Traffic Matrices (TMs). The cost models concerning CapEx and power are presented next.

3.1 Networks and Traffic

To test the effectiveness of the proposed approaches, we consider two different physical networks: the Abilene (Fig. 1) and the Germany17 (Fig. 2). The Abilene physical supply topology consists of 12 nodes and 15 physical links. The Germany17 physical supply topology is composed of 17 nodes and 26 physical links, resulting in a larger average node degree (3.06) than the Abilene topology (2.5). Similarly as in [13], the set $P_{(i,j)}$ of paths for potential lightpaths between every node pair $(i, j) \in V \times V$ was precomputed for each network. The total length of each physical path was limited to 3000 km using the spherical distance for physical link lengths. This corresponds to 72 physical paths for Abilene and 6533 paths for Germany17.

The choice of the considered networks is determined by the availability of the traffic data and their size due to computational complexity of the MILPs (see Section 2). We use the TMs available at [20], and generate for each network an undirected maximum TM [13]. We consider the period between 2004-07-01 and 2004-07-31 for Abilene (time granularity of the original TMs is 5 min.), and the period between 2004-01 and 2004-12 for Germany17 (time granularity of the original TMs is 1 month). The original TMs are then

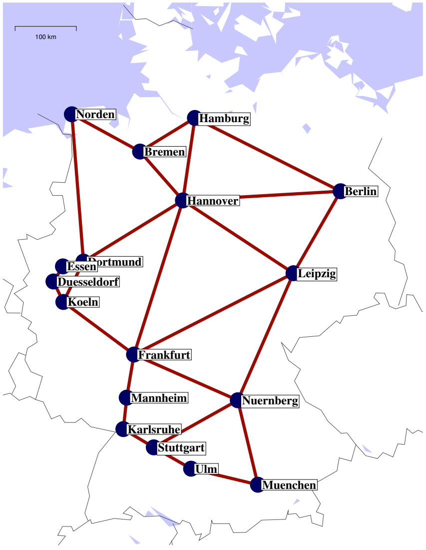


Figure 2: Physical supply topology of the Germany17 network.

rescaled to mimic current traffic volumes. We introduce *total demand per node* being $\sum_{i<j} d_{ij}/|V|$ in order to load both networks with comparable traffic. In particular, we consider three different traffic levels by scaling up the original TMs so that the total demand per node is equal to 100, 300 and 500 Gbps, respectively. We introduce the unit Gigabit per second per node (Gpn), and use it consistently in the rest of the paper.

3.2 CapEx Model

The CapEx model for the IP and WDM layers is based on [10]. Focusing on the IP layer, we model the cost of base nodes (routers consisting of Line Card Shelves (LCSs) and potentially Fabric Card Shelves (FCSs)) and gray line cards (consisting of slot cards and port cards) with muxponders. At the WDM layer, we consider the cost of Optical Line Amplifiers (OLAs), Dynamic Gain Equalizers (DGEs), WDM terminals, and Dispersion Compensating Fibers (DCFs). Note that the costs of OXCs are mapped to the costs of fibers.

The cost β^e of each fiber installed on a physical link $e \in E$ is given by:

$$\beta^e = N_a^e \cdot \beta^a + 2 \cdot \beta^t + N_d^e \cdot \beta^d + L^e \cdot \beta^f \tag{7}$$

where $N_a^e = \lfloor L^e/80 \rfloor$ is the number of OLAs needed to regenerate the signal at edge $e \in E$ given the physical link length L^e in kilometers. β^a is the cost of a single amplifier, β^t is the cost of a single WDM terminal, $N_d^e = \lfloor L^e/320 \rfloor$ is the number of DGEs needed to condition the signal, β^d is the cost of the DGE, and β^f is the cost of each kilometer of DCF.

Table 1 reports the CapEx costs for the components related to the costs of fibers and line cards. Table 2 contains the set of available routers (various configurations of Cisco CRS-1) with the CapEx costs in the third column.

3.3 Power Model

We then consider the power consumption, using realistic power values collected in [9, 12]. In the IP layer, we assume that the power consumption of a colored line card is equal to 500 W (4-port WDM-PHY Physical Layer Interface Module (PLIM) + Modular Services Card (MSC)). Two line cards are needed to realize a bidirectional lightpath. Power consumption of available routers is presented in Table 2 (last column).

Table 2: Set of available routers [10, 12]

SHELF TYPE	CAPACITY [Mbit/s]	CapEx [unit]	POWER [kW]
SH-IP-640	640000	16.67	2.92
SH-IP-1280	1280000	111.67	14.94
SH-IP-1920	1920000	140.83	17.86
SH-IP-2560	2560000	170	20.78
SH-IP-3200	3200000	199.17	23.7
SH-IP-3840	3840000	228.33	26.62
SH-IP-4480	4480000	257.5	29.54
SH-IP-5120	5120000	286.67	32.46
SH-IP-5760	5760000	315.83	35.38
SH-IP-6400	6400000	398.33	47.40
SH-IP-7040	7040000	427.5	50.32
SH-IP-7680	7680000	456.66	53.24
SH-IP-8320	8320000	485.83	56.16
SH-IP-8960	8960000	515	59.08
SH-IP-9600	9600000	544.17	62
SH-IP-10240	10240000	573.34	64.92
SH-IP-10880	10880000	602.51	67.84
SH-IP-11520	11520000	631.68	70.76
SH-IP-12160	12160000	714.18	82.78
SH-IP-12800	12800000	743.35	85.7
SH-IP-13440	13440000	772.52	88.62
SH-IP-14080	14080000	801.69	91.54
SH-IP-14720	14720000	830.86	94.46

In the WDM layer, fewer WDM components contribute to the total cost in comparison to CapEx, since the DCFs and DGEs consume a negligible amount of power. Hence, the total power consumption of each fiber is given by:

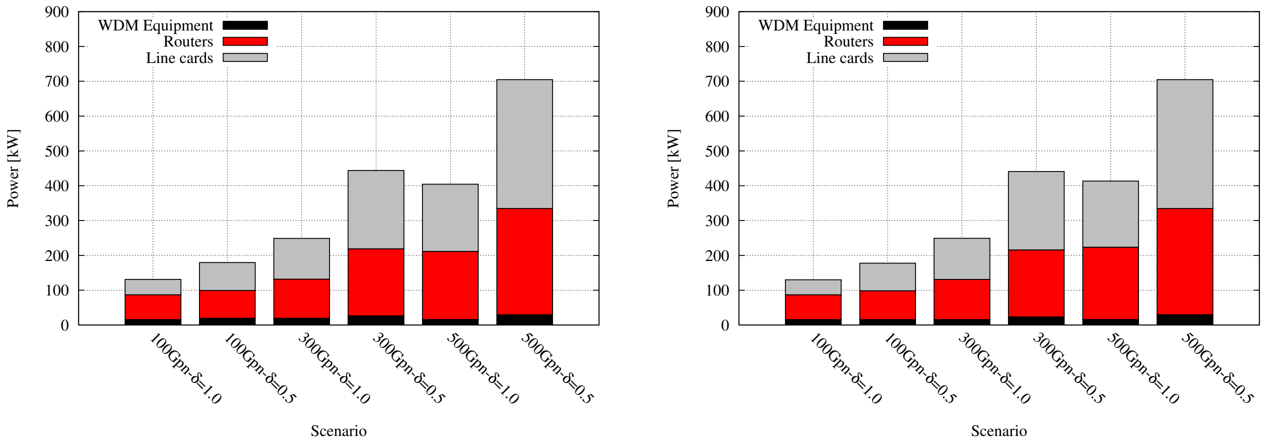
$$\beta^e = N_a^e \cdot \beta^a + 2 \cdot \beta^t \tag{8}$$

Since different power values are available in the literature for β_a and β_t (see [9, 12] for an overview), we set two different pairs of values (see Table 1). These pairs correspond to (*i*) the reference values from Table 4 of [9], and to (*ii*) high values from Tables 8 and 9 of [12]. In this way we cover a realistic range of power consumption of the WDM devices.

4. RESULTS

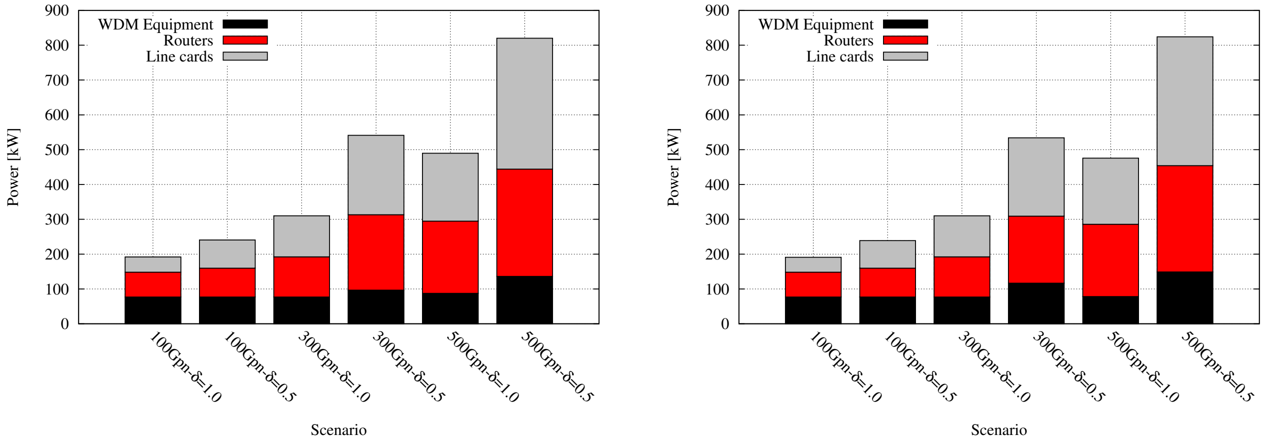
Summarizing the models and parameters varied in our study, we considered two routing assumptions (SPR and splittable MCF), two objectives (minimization of CapEx and minimization of power), two physical supply networks (Abilene and Germany17) with corresponding TMs, three load assumptions (total demand per node equal to 100, 300 and 500 Gpn), two values of maximum admissible utilization δ (0.5 and 1.0), two pairs of power values of an OLA and a WDM terminal ((*i*) $\beta^a = 110\ W, \beta^t = 240\ W$, (*ii*) $\beta^a = 622\ W, \beta^t = 811\ W$). We solved all the optimization problems using CPLEX [11] installed on a high performance cluster [7] composed of 128 Central Processing Unit (CPU) cores with 568 GB of total memory. The time limit was set to 24 hours for SPR optimization problems, and to 2 hours for MCF problems.

All Abilene MCF problems were optimally solved (gap lower than 1 %). The gap exceeded 6 % only for three SPR instances



(a) Power minimization (b) CapEx minimization

Figure 3: Breakdown of power consumption for the Abilene network with $\beta^a = 110$ W, $\beta^t = 240$ W.



(a) Power minimization (b) CapEx minimization

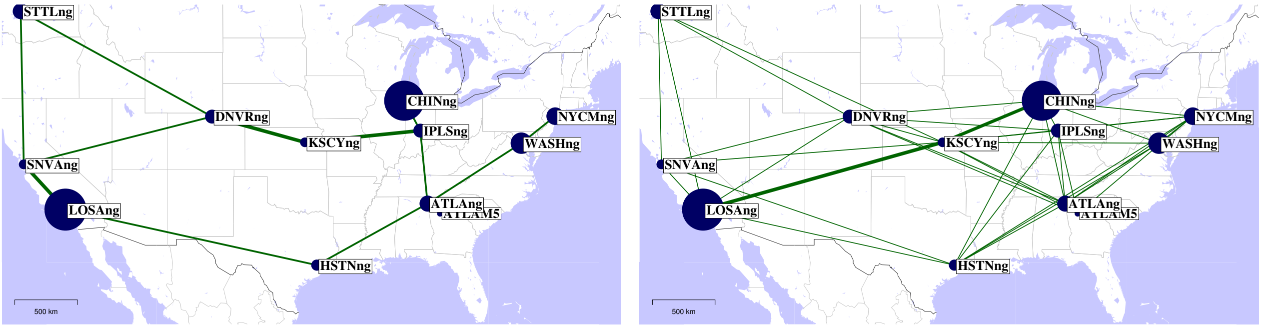
Figure 4: Breakdown of power consumption for the Abilene network with $\beta^a = 622$ W, $\beta^t = 811$ W.

(max. 9 %). Bigger size of the Germany17 network resulted in larger gaps. Only one MCF instance reached 10.37 % of gap, the rest being under 6.08 %. Gaps in the range 6.75-29.73 % were reached for the SPR instances on the Germany17 network.

In the analysis of results (unless stated otherwise) we focus on the Abilene network, since the obtained results are close to optimal, and on SPR as representing common and realistic routing assumption.

Power consumption in IP and WDM layers Fig. 3 reports the power consumption of network components, considering the different scenarios using power minimization (a) and CapEx minimization (b) as objectives. As expected, the total power consumption raises with the traffic increase, since many devices need to be deployed to meet the traffic demands. The increase of power consumption is however slower than the increase of traffic. The maximum admissible utilization δ also plays a crucial role for the power consumption of the network: for the 300 Gpn case, the total power consumption is more than 400 kW with $\delta = 0.5$, with a percentage increment of more than 45 % with respect to the power consumed with $\delta = 1.0$. The restriction of utilization of the bandwidth installed on physical paths can be regarded as the increase of traffic. Then, the figure details also the breakdown of power consumption over network components. The largest amount of power consumption is due to routers and line cards, rather than WDM equipment. Moreover, while the power consumption of WDM equipment presents only minor increase with the load increase, the total power consumption of routers and line cards passes from around 130 kW with 100 Gpn and $\delta = 1.0$ to almost 700 kW with 500 Gpn and $\delta = 0.5$. This suggests that traffic needs should be carefully estimated when deploying the network to avoid large overprovisioning and large wastes of energy consumption. Power consumed by line cards is comparable to the power consumed by router chassis, which indicates high potential of power saving when deploying sleep modes [13].

Power consumption of the network designed with the objective of power minimization (Fig. 3(a)) is almost identical to the power consumed by the CapEx minimized network (Fig. 3(b)). The minor differences can be explained with the gaps of solutions of the MILPs. For example, considering the scenario 500Gpn-δ=1.0 the gap is 4.57 % for power minimization (Fig. 3(a)) and 3.17 % for CapEx minimization (Fig. 3(b)), what results in a slightly higher total power consumption of the CapEx minimized network that the



(a) Physical topology

(b) Logical topology

Figure 5: Physical and logical topologies of the Abilene network designed with power minimization, 300 Gbps per node, $\delta = 0.5$, $\beta^a = 622$ W, and $\beta^t = 811$ W.

power minimized network. The fact that the networks designed with two different objectives consume almost the same amount of power is due to the fact that, nowadays in general, a network component with high CapEx normally consumes also a lot of power.

To give more insight, Fig. 4 reports the results with $\beta^a = 622$ W and $\beta^t = 811$ W. Power consumption of the WDM equipment is still much lower than in that of the IP layer at high loads. At low loads, the physical topology is a tree, and fibers need to be installed in order to guarantee connectivity in the WDM layer. While equipment of smaller capacity is installed at the IP layer, the fibers and WDM equipment remains underutilized consuming comparable power as routers and line cards. Power consumed by the CapEx minimized and power minimized networks are again almost identical (compare Fig. 4(a) and Fig. 4(b)).

Fig. 5 reports a graphical visualization of the physical and logical topologies for power-minimized Abilene network under medium load 300 Gpn with $\delta = 0.5$, $\beta^a = 622$ W, and $\beta^t = 811$ W. The size of the nodes correspond to emanating traffic demand, while the thickness of lines is proportional to the number of installed fibers on a physical link, or lightpaths between a pair of logical nodes. The physical topology evolves with increasing load from a tree to a mesh. For the scenario shown in Fig. 5(a) the physical topology uses 13 physical links out of 15 possible ones, and the resulting topology is similar to the original supply network of Fig. 1. On the contrary, the logical topology (Fig. 5(b)) is quite different from the physical one, since many direct connections are preferably deployed. Moreover, several parallel lightpaths are installed between Chicago and Los Angeles, since large amount of traffic is exchanged between these two cities. Note that there is no direct logical link between Chicago and Los Angeles since the distance between these nodes exceeds the maximum length of a lightpath (3000 km).

We then consider the Germany17 network. Fig. 6 reports the results obtained with power minimization considering the different power consumption values for OLAs and WDM terminals. In this case, the total power consumption of the network is comparable the Abilene network. For example, with $\beta^a = 622$ W, $\beta^t = 811$ W, 500 Gpn and $\delta = 0.5$ the Germany17 network consumes almost 800 kW, similarly to the Abilene network. However, the power share of fibers is lower than in the Abilene case, since the physical links of Germany17 are much shorter, and require fewer OLAs. The power consumption of line cards and routers, on the other hand, is bigger in the Germany17 case. To explain better this issue, Fig. 7 reports the physical and logical topology with 300 Gbps per node, $\delta = 0.5$, $\beta^a = 622$ W, and $\beta^t = 811$ W and power minimization. The physical topology (Fig. 7(a)) uses 22 physical links out of the 26 available ones. The logical topology is highly meshed especially at the Frankfurt node (see Fig. 7(b)), since a lot of traffic is originated from and targeted to it. Concentration of traffic at one node results in a need of routers of high capacities (and high power consumption), as discussed next.

Installed routers In the following, we investigate the type of routers that are installed in the network, starting from Abilene. Fig. 8(a) reports the breakdown of routers considering the different scenarios. Interestingly, many low capacity (and consequently low powered) routers are installed (mostly SH-IP-640). Then, higher capacity devices are used as traffic increases and δ decreases. However, low capacity devices are still used, with SH-IP-640 and SH-IP-1280 representing the 50 % of installed devices even with 500 Gpn and $\delta = 0.5$. We then consider the Germany17 network, reported in Fig. 8(b). Differently from the Abilene case, the set of installed routers is more diversified due to the high concentration of traffic in Frankfurt.

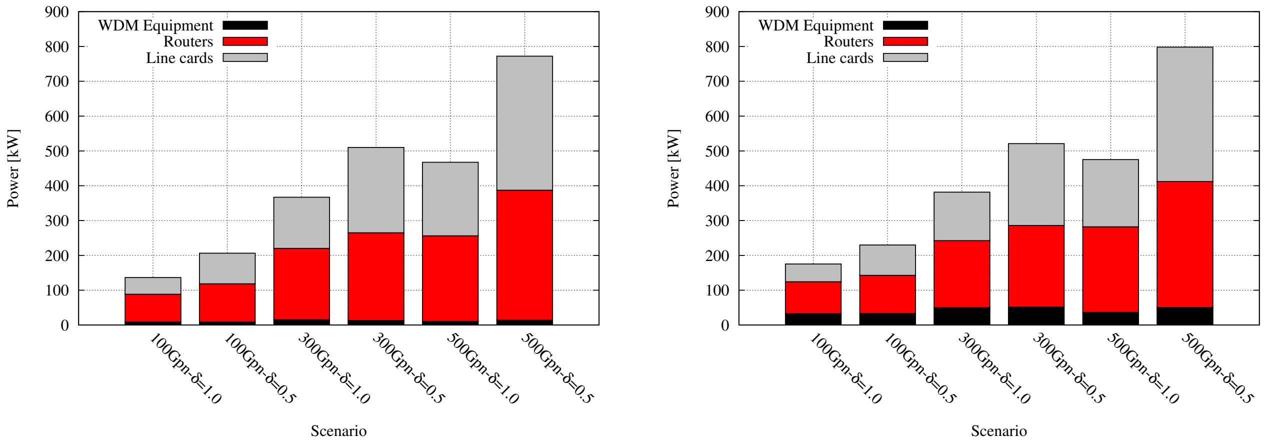
Influence of routing on power consumption We consider the impact of routing on the total power consumption comparing the SPR results with the MCF ones. Clearly, the MCF problem (Section 2.2) is a relaxation of SPR (Section 2.1), since it adopts fluid routing. In fact, while the MCF problem can be taken as a lower bound for power consumption, the SPR problem is more realistic. Thus, a natural question is then how high is the performance loss of SPR with respect to MCF. To precisely capture this effect, we introduce two metrics: the increase of the number of lightpaths Δ_L, and the increase of power Δ_P. Both metrics are expressed in percent in respect to the network using MCF. We define the number of lightpaths obtained solving MCF and SPR as L^{MCF} and L^{SPR}, respectively. We then define Δ_L as:

$$\Delta_L = \frac{L^{SPR} - L^{MCF}}{L^{MCF}} \cdot 100 \qquad (9)$$

In a similar way, we define the total power consumption P^{MCF}, P^{SPR} and Δ_P as:

$$\Delta_P = \frac{P^{SPR} - P^{MCF}}{P^{MCF}} \cdot 100 \qquad (10)$$

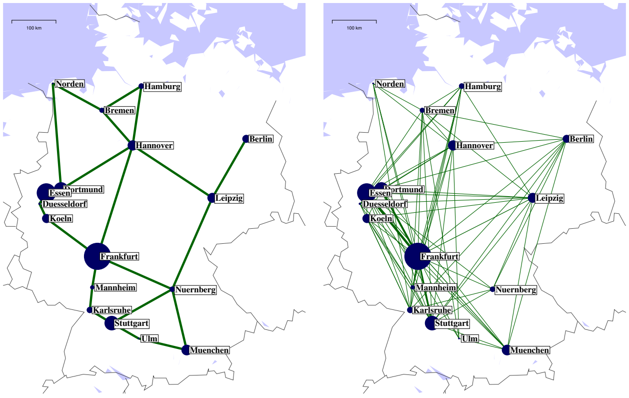
Fig. 9 reports the results for the power-minimized Abilene network, detailing Δ_L (Fig. 9(a)) and Δ_P (Fig. 9(b)). Interestingly, Δ_L never exceeds 10 %, and its trend is almost decreasing for the scenarios in which more capacity is required. This suggests that the number of lightpaths is very similar for both MCF and SPR. Moreover, Δ_P is lower than 11 % for all cases, suggesting that SPR marginally impacts the power consumption.



(a) $\beta^a = 110$ W, $\beta^t = 240$ W

(b) $\beta^a = 622$ W, $\beta^t = 811$ W

Figure 6: Breakdown of power consumption for the Germany17 network with power minimization



(a) Physical topology

(b) Logical topology

Figure 7: Physical and logical topologies of the Germany17 network with power minimization, 300 Gbps per node, $\delta = 0.5$, $\beta^a = 622$ W, and $\beta^t = 811$ W.

Finally, we compare MCF and SPR applied to the Germany17 network, as reported in Fig. 10. Differently from the Abilene case, here SPR has a large impact on Δ_L, requiring even more than 30 % of additional lightpaths with respect to MCF (Fig. 10(a)). However, power consumption using SPR is at most 26.5 % higher than when using MCF (Fig. 10(b)). These values are however influenced by the optimization gaps, which are larger for the SPR solutions than for the MCF ones. We therefore expect that Δ_L and Δ_P would be even smaller with lower SPR optimization gaps.

5. RELATED WORK

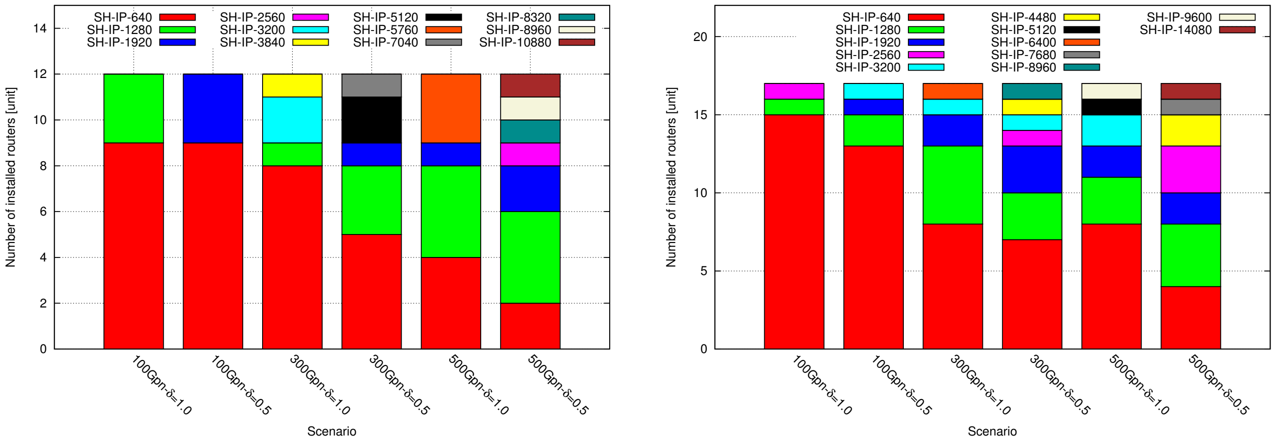
Starting from the seminal work of Gupta and Singh [8], different works have targeted energy-efficient networking (see [2, 3, 13, 24] for overviews). Focusing on the design of power efficient optical networks in the context of CapEx minimized networks, the works that are the closest to ours are [16, 18, 19]. In particular, in [16] the authors focus on two network architectures (IP-over-WDM with gray interfaces and IP-over-Optical Transport Network (OTN)-WDM), providing a break down of normalized power consumption over the IP equipment and OXCs/Electrical Cross-Connects (EXCs). The authors find out that a CapEx minimized network can simultaneously be power optimal for both current and future equipment without sleep modes. Our work corroborates the intuition of [16], but adopting more realistic parameters, i.e., showing the tradeoffs that emerge when traffic originating from measurements is used.

In [19] authors present a model for multi-layer network design. They consider two types of line cards with gray interfaces, diversified lightpath capacities, multiple chassis configurations, and Routing and Wavelength Assignment (RWA). Differently from our work, the authors do not consider fiber installation, and traffic demands are randomly generated. Moreover, due to the complexity of the formulated MILP, the problem is optimally solved on a small network composed of 6 nodes and 7 fibers, each of them supporting 3 wavelengths. According to [19], power-efficient network design can decrease the power consumption of multi-layer networks compared to CapEx efficient network design. The main reason for this reduction is the assumption that power consumption of the network depends on traffic, while CapEx does not. In particular, authors adopt the power values of [4] but their CapEx values are unreferenced.

Finally, Shen and Tucker present a network design model in [18]. Their MILP minimizes power of the network, and determines the number of fibers installed on a physical link, established lightpaths and their routing, as well as routing of IP traffic. Differently from our work, various router configurations are not considered. Moreover, relatively high power per IP port (1000 W) was assumed following an indirect derivation from Cisco CRS-1 data sheet. CapEx values are explicitly given, but unreferenced. Optimal solution is achieved only for a small network (the same as in [19]) with fibers accommodating 16 wavelengths. As a result, the network design with different optimization objectives shows almost the same network design costs. The authors point out however, that this conclusion may not be valid if a component with low power consumption is the most expensive one.

6. CHALLENGES FOR GREEN DESIGN

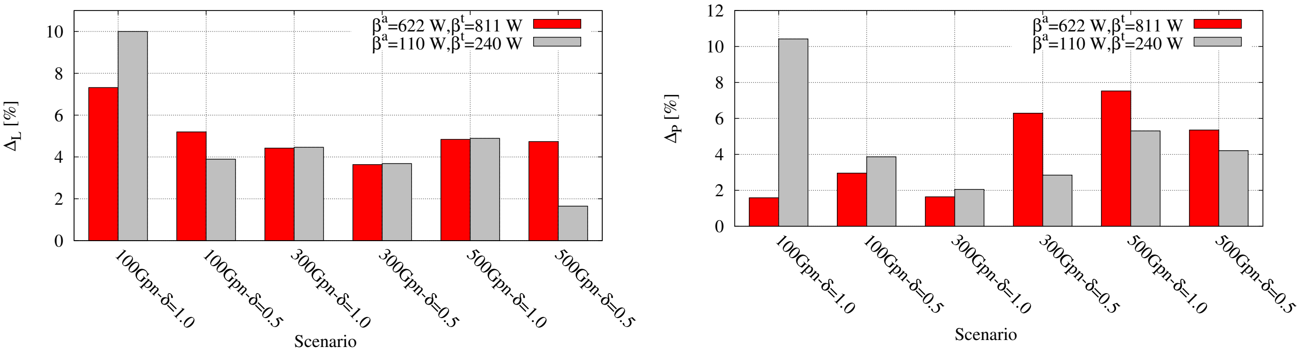
The obtained results prove that it is possible to design an optical network minimizing the power consumption. However, an Internet Service Provider (ISP) might have different objectives and constraints that are considered during the design phase. In particular, networks are designed to be resilient in case of failures, being able to guarantee connectivity even if some links in the topology fail. Moreover, MPLS tunnels may be considered at the top of the



(a) Abilene network with power minimization

(b) Germany17 network with power minimization

Figure 8: Installed routers (routers are ordered by ascending capacity and cost).



(a) Increase of the number of lightpaths

(b) Increase of power

Figure 9: Comparison of networks designed with SPR and MCF models for the Abilene network with power minimization.

logical topology. Finally, physical constraints may hold – it may e.g. be impossible to install high-end devices in all sites or the network cannot be entirely cabled with high-capacity fibers. All the previous issues can be solved in our MILP by modifying the initial formulation. However, we recognize that the results might be impacted by the specific objective and constraints adopted.

Another issue of the presented work is the integration with Operational Expenditure (OpEx) [22]. One of the contributors to OpEx is the electricity cost due to device usage. In particular, current network equipment consumes a static amount of power, independently from the device load. This means that the associated electricity cost is constant, and hence it is reasonable to minimize power consumption (and consequently electricity cost) during the design. However, devices with power saving modes are currently under development [23]. In this scenario, minimizing only power for the worst case traffic may not be the best solution, since the power consumption of devices may vary over time in the future. Consequently, it is possible to reduce the network power consumption when traffic is low, as detailed in our previous works [5, 6]. For example, it might be more convenient to use many devices that can be switched off during night-time than installing few constantly powered on devices. This issue can be solved by considering jointly the design and the management of the network, i.e. modifying the presented MILP by considering the variation of traffic and the possibility that devices are able to adapt power with load.

7. CONCLUSIONS

We have investigated the problem of cost-efficient design of IP-over-WDM networks, through explicitly targeting the minimization of power consumption. Differently from the models already presented in the literature, we have taken into account realistic routing constraints, and realistic parameters. Results, obtained over an extensive set of scenarios and networks, indicate that our model is still cost-efficient, being the total power consumption at most 26.5 % higher than the previous models. Moreover, we have found that most of the power in an IP-over-WDM network is consumed by routers and line cards, even when high power consumption of OLAs and WDM terminals is assumed. Finally, we have provided a detailed characterization of deployed devices.

As next steps, we plan to study the design problem adopting next generation devices, whose power consumption will be more energy proportional with load. Moreover, we want to assess how much the introduction of sleep mode capabilities in the IP layer impacts the design phase.

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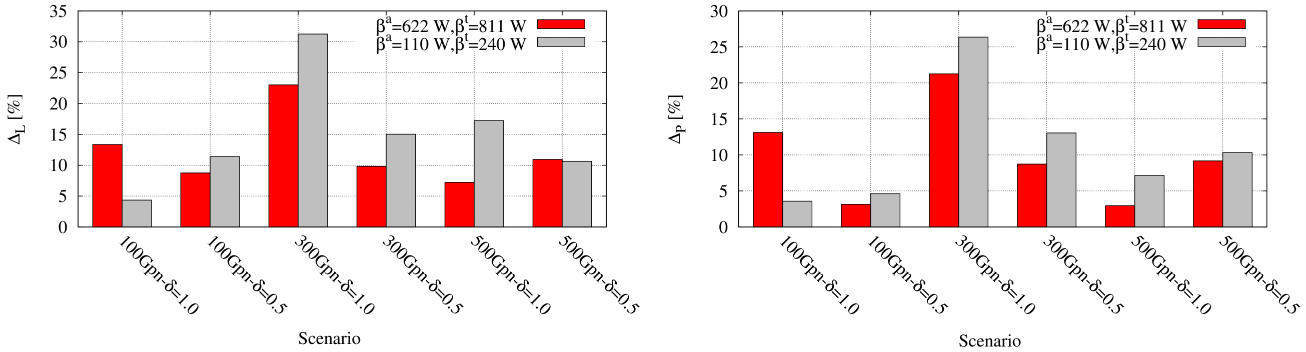

(a) Increase of the number of lightpaths

(b) Increase of power

Figure 10: Comparison of networks designed with SPR and MCF models for the Germany17 network with power minimization.

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