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Algorithms for the Multi-Period Power-Aware Logical Topology Design with Reconfiguration Costs

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***Abstract*—We tackle the problem of reducing power consumption in the Internet Protocol (IP)-over-Wavelength Division Multiplexing (WDM) networks, targeting the power-aware Logical Topology Design (LTD). Unlike the previous work in the literature, our solution minimizes the power consumption and the cost (in terms of reconfigured traffic) incurred when the network is reconfigured. We first formulate the LTD with reconfiguration costs as an optimization problem. Then, we present three heuristics to effectively solve it. We compare our algorithms over an extensive set of realistic networks and scenarios. Results indicate that our algorithms are effective in reducing power consumption while limiting the amount of traffic which is reconfigured. Moreover, we show that the input parameters are intuitive and easy to set, which makes our algorithms more practical.**

***Index Terms*—Optical Networks, Energy-Efficiency**

I. Introduction

Recent studies show that the Information and Communication Technology (ICT) sector is responsible for a significant percentage of the worldwide power consumption. According to estimations in [1], the worldwide operations of network equipment accounts for 25 GW (yearly average) of the total ICT consumption. While the joule/bit in telecommunication networks is decreasing with time, the joule/user keeps steadily increasing.

In this context, as the traffic volume increases and access solutions shift from x Digital Subscriber Line (xDSL) to Passive Optical Network (PON), the major fraction of power consumption is moving from access to backbone networks [2]. Hence, the design of energy-efficient backbone networks becomes essential to reduce power requirements of the future Internet. Today's core segments of the networks are usually implemented using Wavelength Routed (WR) optical networks. Traffic in WR networks is carried by optical circuits, called lightpaths, which are optically switched at intermediate nodes without the need of electronic processing. The design of WR networks requires solving both the LTD (in which the set of lightpaths is determined given certain traffic demands and their routing scheme) and the Routing and Wavelength Assignment (RWA) (in which the lightpaths are routed over the physical topology).

In this work, we focus on a multi-period approach for the LTD of the network. In particular, we exploit the traffic variability in order to configure the network in a more energy-efficient manner. The intuition is to allow to switch off unnecessary resources in low demand periods achieving energy savings. However, a drawback of this approach is that the network has to be reconfigured between two subsequent time periods. Frequent and regular reconfigurations may cause a deterioration of the Quality of Service (QoS) perceived by the users, since the reconfiguration time is non-negligible. For this reason, we present a solution to reduce the power consumption with consideration of the amount of traffic that is reconfigured. In this way, while being energy-efficient, the negative effect of frequent reconfigurations is limited. In detail, we define three heuristics to solve the problem, and compare them over an extensive set of scenarios, adopting as realistic assumptions as possible on network topologies, traffic, Capital Expenditures (CapEx) and power values.

The problem of reducing power consumption with consideration of reconfiguration costs in terms of reconfigured traffic has been first presented in our previous work [3]. The main differences of this work with respect to [3] are the following. First, we corroborate the set of algorithms of [3] by introducing a new heuristic to efficiently solve the problem. Second, we extend our analysis over different networks. Third, we consider explicitly the constraints on the installed devices coming from the design of the network. Fourth, the network that the algorithms start with is designed using different (past) traffic data than the (future) traffic used for evaluation of the energy savings. Fifth, we define a new set of metrics to assess the algorithm performance. Finally, we extend our analysis with a sensitivity analysis of the algorithms to their parameters.

The paper is organized as follows. Section II reviews related and previous work. The general approach that we propose is presented in Section III. The algorithms to solve the Multi-Period Power-Aware LTD (MP-PA-LTD) are described in Section IV. The considered scenarios are described in Section V. Evaluation metrics are reported in Section VI. Section VII reports the complete set of results. Discussion and implementation issues are reported in Section VIII. Finally, conclusions are drawn in Section IX.

II. Related and previous work

The design of a Logical Topology (LT) realized by the optical network has been widely tackled by the research community so far [4], [5]. We first review the LTD approaches exploiting the temporal variation of traffic, but not aiming at the energy saving. Then, we move to the solutions reducing power consumption of the network.

A. Non-power aware Approaches

LTD had been a topic of research since long before the green networking era. We survey selected works focusing on the exploitation of traffic variation and reconfiguration aspects.

Two heuristic approaches targeting minimization of the average hop distance (Maximizing Single-Hop Traffic and

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Maximizing Multihop Traffic) are proposed in [6]. A complementary method is proposed in [7]. The usage of an auxiliary graph is considered in [8]. Reconfiguration issues in traffic adaptive broadcast and multihop WDM networks are studied in [9] and [10], respectively. The reconfiguration policies are formulated as a Markovian decision process, and a heuristic is proposed and evaluated. Algorithms for the reconfiguration are studied in [11] (Branch-Exchange Sequences), [12] (meta-heuristics) and [13] (Longest lightPath First, Shortest lightPath First, and Minimal Disrupted lightPath First).

The work [14] by Narula-Tam and Modiano proposes a multihop network reconfiguration strategy that makes a small change to the LT at regular intervals in order to reduce the network load.

More recent studies include [15], where a two step reconfiguration Fuzzy Metric Reconfiguration Algorithm (FMRA) is proposed. A Tabu-search heuristic is proposed in [16] as alternative to complex Mixed-Integer Linear Problems (MILPs) for the Scheduled Virtual Topology Design (non-reconfigurable and reconfigurable). Lagrangian relaxation of the planning problem is first proposed in [17] and then extended in [18]. Eventually, Greedy Approach with Reconfiguration Flattening (GARF) utilizing also the Tabu-search meta-heuristic is proposed in [19]. Finally, the concept of domination between Traffic Matrices (TMs) is proposed for large problem instances in [20], [21].

An adaptive solution based on watermarks has been introduced in [22] and extended in [23]. Multi-layer virtual topology design taking into account multiple periods and physical layer impairments are tackled in [24]. Finally, a distributed algorithm for dynamic LT reconfiguration using Lagrange multipliers is proposed in [25].

All of these works exploit the reconfigurability feature of optical networks, without directly taking into account the reduction of power consumption.

B. *Power-aware Approaches*

The energy saving schemes influence the LT as network elements are put into sleep mode or are completely switched off. There are several works in the field of green networking that consider networks under different load (refer to [26], [27], [28], [29] for an overview). However, only a few works consider the traffic variation in addition to the different load scenarios.

The authors of [30] investigate a Power-Aware Traffic Engineering (GreenTE), by proposing MILP coupled with methods to reduce its complexity. In particular, the concept of balancing the load in the "greened" network is proposed, and the signaling issues are thoroughly discussed. QoS is investigated using link utilization, delay, queue length (with ns-2 simulations), and number of MultiProtocol Label Switching (MPLS) tunnels. Reconfiguration aspects and the constraints of the WDM layer are not considered.

The authors of [31] eliminate rerouted traffic at the IP layer by introducing a layer 2 topology. An Energy-Aware Router architecture is also presented. However, this solution introduces a new level in the control plane architecture, and the rerouting takes place at the layer 2.

The QoS-aware energy optimal network topology design is tackled in [32], where a *Depth d Search Algorithm* is proposed and implemented in MiDORi (Multi-(layer, path and resources) Dynamically Optimized Routing) Network

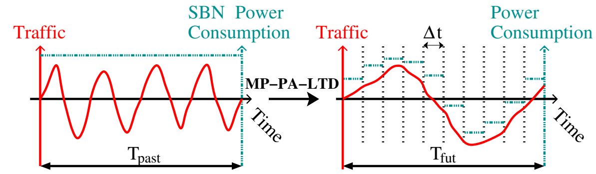


Fig. 1. Main idea of MP-PA-LTD (mind different scales of x-axes).

Architecture. The algorithm checks the fulfillment of the QoS requirements, but the reconfiguration cost is not taken into account. The authors of [33] perform a reality check of Energy-Aware Routing on different network scenarios assuming three different energy models (energy-agnostic, idleEnergy and fully proportional). The constraints on maximum load on logical links are incorporated in the formulated MILP, and analyzed in the solutions. The MILP does not take into account reconfiguration costs. Minimization of power consumed by router Line Cards (LCs) and chassis in each of 12 periods over a day is investigated in [34]. The authors analyze the newly turned-on and shut down LCs (and lightpaths), as well as the percentage of traffic rerouted in the Virtual Topology that is produced as outcome of the MILP solution. The reconfiguration cost is however not included in the objective function of the formulated MILP.

A design of a complete IP-over-WDM network has been presented in our previous work [26]. Updates of the network configuration (including LT) for energy saving assuming different levels of freedom of rerouting in the IP and WDM layers are discussed. The reconfiguration cost is not included in [26], since this work targets the assessment of the potential of energy saving in IP-over-WDM networks.

Performance of switch-off and switch-on schemes are compared in [35]. The authors propose a network designed for off-peak hour with the possibility to establish dynamic optical circuits in the peak hour. Then, routing parameters are introduced to trade between energy consumption and route changes. Solutions of the formulated MILPs are presented, without investigating practical heuristics.

Distributed algorithms are proposed in [36] (GRiDA), [37] (utilization of periodic Link State Advertisements (LSAs) describing configuration and load of links, and broadcasting critical states) and in [38] (Distributed and Adaptive Interface Switch off for Internet Energy Saving (DAISIES)). The reconfiguration cost in terms of rerouted traffic is considered in none of these works, while the number of reconfigurations per node is analyzed in [36], [37].

All the works presented above are focused on the reduction of power consumption assuming a temporal variation of traffic, without directly targeting the reduction of the reconfiguration costs. To solve these issues, in this work we tackle explicitly the minimization of the weighted sum of power consumption and reconfiguration costs. In particular, we start from our works [39] and [40] to redesign our previous algorithms by considering also the reconfiguration costs. Moreover, we propose a new algorithm, called Energy Watermark Algorithm (EWA) [41], which is fully adaptive and makes decisions about establishing and releasing lightpaths. In this way, we are able to compare different algorithms, and discuss deeply the trade-off between power consumption and reconfiguration costs. Additionally, we evaluate our algorithms on as realistic scenarios as possible. Finally, we differentiate between past and future traffic respectively

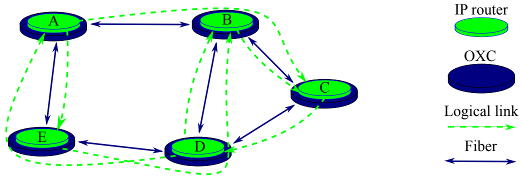


Fig. 2. Network model on exemplary logical and physical topologies.

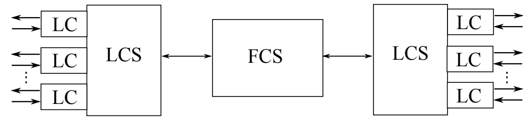


Fig. 3. IP router model – configuration with 2 LCSs and a FCS.

used for the design of the Static Base Network (SBN), and for evaluation of the energy savings achieved with heuristics starting from the SBN. While the terms 'virtual' and 'logical' are used interchangeably in the related work, we consistently use the term 'logical' in this work.

III. Multi-Period Power-Aware Logical Topology Design

In the MP-PA-LTD, we exploit the dynamic nature of traffic, which is not constant in time, but usually follows a day-night pattern with high traffic demands during the day and low traffic demands during the night. Today, network resources are allocated to constantly satisfy the maximum demands. These resources consume energy even if not used or underutilized. Indeed, power consumption in currently deployed network devices is basically independent of load [42]. Therefore, we divide the day into smaller time periods. Each period is characterized by a TM used to design the LT for the current period. Configuring the network for each of these periods allows utilization of resources to a higher extent, and consequently power can be saved by switching off some devices. Fig. 1 reports a schematic description of our solution. Normally, power consumption of the network is constant, independently of the current traffic (Fig. 1 left). With our approach, instead, the network power consumption is wisely adapted for each time period (Fig. 1 right). However, the network configuration (network nodes with installed devices in active or inactive states, established lightpaths, and routing of traffic demands) has to be changed between two consecutive time periods. Reconfiguring means adding or deleting lightpaths from the LT, which involves changing the routing of the traffic over the LT. In this work we consider the latter as a metric to quantify the reconfiguration costs. Therefore, we define the reconfiguration cost for each lightpath as the amount of new traffic that has to be routed on the lightpath at the beginning of the new time period. All the notation used in this work is summarized in Appendix VIII.

A. Network and node model

We consider a backbone IP-over-WDM network schematically modeled in Fig. 2. Fibers (blue solid lines) interconnect Optical Cross-Connects (OXCs) at the physical layer. They are used to realize the LT at the IP layer. We model the LT as a directed network composed of nodes and logical links (green dashed lines). A logical link consists of all the lightpaths established between a corresponding pair of IP routers, independently of their realization in the physical topology.

Each IP router has a modular structure, and is composed of one or more Line Card Shelves (LCSs) interconnected by Fabric Card Shelves (FCSs), as depicted in Fig. 3. The LCS is the basic structure of the router. It is composed of the router chassis, switching fabric, cooling and power supply systems. It implements the control plane and data plane software. Furthermore, it is equipped with LCs which are responsible for the physical connectivity of the router. Colored router interfaces are assumed. In the case that two or more LCSs are required, the FCSs are essential to interconnect the LCSs. Indeed, the FCSs contain the switching fabrics that are used for the interconnections of the LCSs. In this work, we target reduction of the power by switching off LCs. This choice is due to the fact that LCs are expected to have significantly lower boot times than LCSs and FCSs, which makes their frequent activation and deactivation possible. We do not consider the power consumption of the OXCs and optical amplifiers since we focus on the LTD. Moreover, powering these devices on and off is expected to be time consuming.

B. Mathematical model

An informal description of the problem we target is the following. **Given** the current network configuration and the set of current traffic demands, **find** the set of lightpaths and corresponding LCs that must be powered on so that the weighted sum of the power consumption and the reconfigured traffic is minimized, **subject to** flow conservation constraints, maximum lightpath utilization constraints, and constraints on the installed devices.

More formally, let us represent the LT of an IP-over-WDM network as a directed graph $H = (V, L)$ where V is the set of all nodes in the network and L is the set of supplied logical links on which lightpaths can be established. Let $L_{(i,j)} \subset L$ denote the set of supplied logical links between node i and node j. We exclude parallel logical links, therefore $|L_{(i,j)}| = 1$ for each $(i, j) \in V \times V$.

Each logical link is formed by a trunk of parallel lightpaths. Let us define the capacity of a lightpath as C. Moreover, we denote by $\delta \in (0, 1]$ the maximum lightpath utilization. Each lightpath needs a transmitter and a receiver located in two LCs installed at the endpoints of the lightpath. The power consumption of a LC is denoted as $\mathcal{P}^{LC}$.

We consider a set of time periods T consisting of past and future time periods ($T = T_{past} \cup T_{fut}$, $T_{past} \cap T_{fut} = \varnothing$). We assume to know the traffic exchanged in the past time periods $T_{past} \subset T$ (Fig. 1 left) and we determine the set of installed devices using this past traffic. We call this procedure Static Base Network (SBN) design. At the end of the SBN design, a set of installed devices is defined. Then we apply the MP-PA-LTD to the SBN on future time periods $T_{fut} \subset T$ (Fig. 1 right). While time periods T_{past} regard the traffic before the SBN design, the future time periods T_{fut} concern future traffic which we assume to be unknown during the SBN design phase. The duration of each time period $t \in T_{fut}$ is denoted as Δt. A Traffic Matrix (TM) $D(t)$ for each time period $t \in T$ contains traffic demands between the nodes $(a, b) \in V \times V$ with values $d^{ab}(t)$. During the MP-PA-LTD constraints of the SBN are checked – the number of powered on devices at each node cannot exceed the number of installed devices.

We define the variables for each $t \in T_{fut}$. The flow variables $f_{ij}^{ab}(t) \in \{0,1\}$ determine whether the traffic demand originated at node a and targeted to node b traverses the logical link from i to j at time t. Let us denote as $r_{ij}^{ab}(t) \in \mathbb{R}_+$ the amount of reconfigured traffic (in Gbps) between a and b on the logical link from i to j at time t. The cost associated with each unit of reconfigured traffic is denoted by $\mathcal{R}$. The setting of $\mathcal{R}$ allows trading between power minimization (low $\mathcal{R}$) and low reconfigured traffic (high $\mathcal{R}$). Thus, given a certain fixed value for $\mathcal{R}$, the solution of the problem represents the best trade-off between the consumed power and the reconfigured traffic. The value of $\mathcal{R}$ has thus to be chosen according to the importance that the network operator gives either to power consumption or to reconfigured traffic. Moreover, let us introduce the variable $y_l(t) \in \mathbb{Z}_+$ denoting the number of lightpaths established on the logical link l at time t. Finally, let $x_i^{LC}(t) \in \mathbb{Z}_+$ be the number of LCs powered on at each node i at time t, which is bounded by the number of installed LCs X_i^{LC} in each node of the SBN.

Given the previous notations, we formalize the MILP for an arbitrary time period t as follows:

Objective:

$$\min \left(\mathcal{P}^{LC} \sum_{i \in V} x_i^{LC}(t) + \mathcal{R} \sum_{i \in V} \sum_{j \in V} \sum_{a \in V} \sum_{b \in V} r_{ij}^{ab}(t) \right) \quad (1)$$

Subject to:

$$\sum_{j \in V \setminus \{i\}} (f_{ij}^{ab}(t) - f_{ji}^{ab}(t)) = \begin{cases} 0 & i \neq a, i \neq b \\ 1 & i = a \\ -1 & i = b \end{cases} \quad , \forall i, a, b \in V \quad (2)$$

$$d^{ab}(t) \cdot f_{ij}^{ab}(t) - d^{ab}(t-1) \cdot f_{ij}^{ab}(t-1) \leq r_{ij}^{ab}(t), \quad \forall i, j, a, b \in V \quad (3)$$

$$\sum_{a \in V} \sum_{b \in V} d^{ab}(t) \cdot f_{ij}^{ab}(t) \leq \delta \sum_{l \in L_{(i,j)}} C \cdot y_l(t), \quad \forall i, j \in V \quad (4)$$

$$\sum_{j \in V} \sum_{l \in L_{(i,j)}} y_l(t) \leq x_i^{LC}(t), \quad \forall i \in V \quad (5)$$

$$\sum_{i \in V} \sum_{l \in L_{(i,j)}} y_l(t) \leq x_j^{LC}(t), \quad \forall j \in V \quad (6)$$

$$x_i^{LC}(t) \leq X_i^{LC}, \quad \forall i \in V \quad (7)$$

Control variables: $f_{ij}^{ab}(t) \in \{0,1\}$, $r_{ij}^{ab}(t) \in \mathbb{R}_+$, $y_l(t) \in \mathbb{Z}_+$, $x_i^{LC}(t) \in \mathbb{Z}_+$

The objective (1) minimizes the weighted sum of the total power consumed by LCs and of the total cost of reconfiguration. The cost of reconfiguration is the quantity of reconfigured traffic, weighed by the constant $\mathcal{R}$. The constraints (2) ensure the flow conservation of the traffic demands over the LT assuming unsplittable demands. The constraints (3) determine the reconfigured traffic between the current time period t and the preceding time period $t-1$.[1] The constraints (4) ensure enough bandwidth on a logical link to accommodate the traffic flows. The inequalities (5) and (6) compute the number of powered on LCs for each node. Finally, the constraints (7) ensure that the number of LCs powered on is lower or equal to the number of installed LCs in the SBN.

[1] $f_{ij}^{ab}(t-1)$ is computed in the previous time period and it is an input parameter for the current time period t.

C. Static Base Network (SBN)

The SBN is the network configuration used as a starting point for MP-PA-LTD. During this step, the sets of installed routers and of LCs are determined. In particular, we use the Genetic Algorithm (GA) proposed in [40] to solve the problem with the objective of CapEx minimization.

The SBN is dimensioned to satisfy the maximum TM D_{SBN}, based on the set of past time periods T_{past}.

$$d_{SBN}^{ab} = \max_{t \in T_{past}} d^{ab}(t), \quad \forall a, b \in V \quad (8)$$

This configuration may not be able to satisfy all future traffic demands, causing link overload and consequently dropping of traffic. For this reason, during the SBN design, we overprovision the network in such a way that the installed resources (LCs, LCSs and FCSs) may eventually sustain the future traffic. The overprovisioning factor γ is defined as the ratio between the lightpath's capacity used during the SBN design and its full capacity. Thus, $\gamma \in (0,1]$. For instance, with an overprovisioning factor of 0.4, the SBN is designed considering that lightpaths can use just 40% of their capacity, meaning that 60% more resources are installed with respect to the expected requirements.

IV. HEURISTICS

The presented MILP falls in the class of NP-hard problems, and therefore finding the optimal solution becomes impractical even for small networks. To overcome this issue, we follow a heuristic approach. In particular, we consider three different heuristics to solve the MP-PA-LTD: Least Flow Algorithm (LFA), GA and EWA, with the last two being adaptive ones. Moreover, our algorithms assume shortest path routing (in terms of IP hops) and unsplittable traffic demands, two common assumptions usually adopted by network operators. Each algorithm returns for period $t \in T_{fut}$ a network configuration defined as network nodes V with $x_i^{LC}(t)$ powered on LCs (out of the installed X_i^{LC} LCs) established lightpaths forming logical links $y_l(t)$, and IP routing of traffic demands $f_{ij}^{ab}(t)$. The rest of this section is devoted to the description of the algorithms.

A. Least Flow Algorithm (LFA)

The LFA targets the minimization of the number of logical links powered on to satisfy a given traffic demand, adopting a modified version of the Least-Flow algorithm proposed in [39], which is designed to work in IP networks. In particular, the logical links with the lowest amount of traffic flowing on them are targeted first. The intuition is that it is simpler to switch off links carrying a low amount of flow rather than a link whose flow is close to the link capacity. Alg. 1 reports a schematic description of the LFA heuristic. In particular, the set of logical links from the SBN Y_l^{SBN}, the current TM $D(t)$ and the maximum link utilization δ are provided as input. At the beginning, the logical links are sorted with increasing flow (line 1). Then, at each iteration, the considered link is removed from the topology (line 3), and traffic is then rerouted on the residual topology (line 4-5). After rerouting, if connectivity and utilization constraints are still fulfilled

Algorithm 1 Pseudo-code of LFA.

Input: Set Y_l^{SBN} from SBN, current TM $D(t)$, maximum utilization δ
Output: Updated netConfig
1: LLs=sortLeastFlow(Y_l^{SBN});
2: **for** $j = 1$; $j \leq$size(LLs); j++ **do**
3: disableLogicalLink(LLs[j]);
4: paths=computeAllShortestPaths($D(t)$);
5: computeAllLinkFlow(paths, $D(t)$);
6: **if** (checkPaths(paths) == false) || (checkFlows(paths, δ) == false) **then**
7: enableLogicalLink(LLs[j]);
8: **end if**
9: **end for**

(line 6), then the selected link is definitively powered off. Otherwise it is left on. The procedure is repeated for all the logical links (line 2). In the case that the current TM cannot be satisfied by the SBN, LFA does not power off any link.

B. Genetic Algorithm (GA)

The GA was first introduced in [40], where it optimizes just the power consumption of the network. It has been adapted to solve the MP-PA-LTD to directly minimize the power consumption and the reconfiguration cost. The GA is a meta-heuristic based on the principles of the natural evolution: the initial population evolves through several generations in which only a subset of the individuals survive from one generation to the following one.

Each individual represents a LT. Only feasible individuals can be part of the population. In particular, an individual is feasible if its corresponding LT satisfies the TM and the constraints (7) on the maximum number of powered on devices. If the GA cannot find any feasible solution, the constraints (7) are relaxed and dummy LCs are installed. However, the traffic routed over these additional LCs is considered as overload.

The individuals survive through generations depending on their fitness value which is defined as the weighted sum of normalized power consumption and normalized reconfiguration cost. Thus, the GA optimizes the same objective (1) as the mathematical model presented in Section III-B. The normalization of the power and of the reconfiguration cost is performed with respect to the possible worst case, i.e., every node has to process all the traffic of the current TM. The sum is weighted by the parameter $\alpha \in [0, 1]$, which is used, similarly to the constant $\mathcal{R}$ of (1), to trade between power and reconfiguration costs.

Alg. 2 describes briefly how the GA works. The algorithm requires as input the network configuration from previous time period $t - 1$ and the current TM $D(t)$. Moreover, three algorithm parameters have to be provided: the maximum number of generations without improvements M, the population size S and the offspring size K. At the beginning, the first population is randomly generated (line 1). After this step the fitness is evaluated (line 3) and the evolution process begins (line 4). At each generation, the reproduction and the selection phases are repeated. In particular, new individuals are created during the reproduction phase (line 5), starting from some other individuals that have been chosen as parents. Then, a new population is created (line 6) by selecting the individuals with best fitness value from the old population and its offspring. At each generation, the best fitness value among all the individuals is selected and stored (line 7). If the fitness has not improved with respect to the previous generation, the current number of generations without improvement is incremented (line 9). The evolution process stops when the fitness value has not improved for more than a maximum number of generations (line 4). At the end, the individual with the best fitness is chosen, and the set of powered on lightpaths is updated (line 15).

Algorithm 2 Pseudo-code of GA.

Input: netConfig from period $t - 1$, current TM $D(t)$, α, M, S, K
Output: Updated netConfig
1: population=generateFirstPopulation($D(t)$, netConfig, S, α);
2: i=0;
3: fitness=evaluateFitness(population, α);
4: **while** ($i \leq M$) **do**
5: offspring=generateOffspring(population, $D(t)$, netConfig, α, K);
6: population=selectPopulation(population, offspring, α, S);
7: newFitness=evaluateFitness(population, α);
8: **if** (newFitness $\geq$ fitness) **then**
9: i++;
10: **else**
11: i=0;
12: fitness=newFitness;
13: **end if**
14: **end while**
15: netConfig=applyConfiguration(population);

C. Energy Watermark Algorithm (EWA)

The EWA is an adaptive algorithm based on [22] which uses a low and a high watermark (W_L and W_H) in order to switch off as many LCs as possible without exceeding maximum utilization of last lightpath on a logical link ψ. Each watermark is defined as a threshold on the utilization of the last lightpath on a logical link. In particular, W_H triggers attempts to establish additional lightpath(s) in order to avoid overload of the network and ensure appropriate QoS. On the contrary, W_L triggers attempts to release lightpath(s) in order to save energy.

The algorithm takes as input the network configuration in previous time period $t - 1$ TM $D(t)$ for the current period t, capacity of a lightpath (WDM channel) C, W_L, W_H and ψ.

Alg. 3 shows the main pseudocode of EWA. The complete algorithm description is reported in [41]. EWA first checks whether all the demands in the current network configuration are routable, and iteratively tries to establish additional lightpaths for the unroutable demands (if any), starting from the largest ones (line 1). The logical links on which watermarks are exceeded are identified next (line 2), and violation of the W_H is checked, starting from the logical links with the highest utilization of the last lightpath (line 3). For each overloaded logical link (from the most overloaded to the least overloaded), the algorithm first tries to increase the capacity of the logical link if a demand with the same source and target nodes flows through it. If this is not the case,

Algorithm 3 Pseudo-code of EWA.

Input: netConfig from period $t-1$, current TM $D(t)$, C, W_L, W_H, ψ
Output: Updated netConfig
1: ensureDemandsRoutability(netConfig, $D(t)$, C);
2: sortedLLsExceedingWMs = getSortedLLsExceedingWMs(netConfig, $D(t)$, W_L, W_H);
3: establishNecessaryLpaths(netConfig, $D(t)$, C, sortedLLsExceedingWMs, W_L, W_H);
4: releaseUnnecessaryLpaths(netConfig, $D(t)$, sortedLLsExceedingWMs, W_L, W_H, ψ);

attempts are made to establish lightpath(s) for the possibly biggest demand flowing over the overloaded logical link.

Once the load is lower than W_H for all logical links, or it is impossible to reduce overload anymore, violation of the W_L is checked starting from the least loaded logical links (line 4). One lightpath at a time is tried to be released, making sure that ψ is not exceeded.

Differently from [22], EWA is able to add or delete more than one lightpath during the execution of the algorithm (lines 1, 3 and 4). Moreover, EWA considers the case in which adding some lightpath(s) does not forbid deleting other lightpath(s). Finally, parameter ψ is added in order to trade between QoS and energy saving. These differences result in a different approach in establishing and releasing lightpaths compared to [22].

V. Scenarios

We first describe the considered networks and the traffic assumptions. Next, we detail the CapEx and power consumption figures of the adopted network components.

A. Networks and Traffic

We consider traffic demands that have been measured in three different networks: Abilene (12 nodes), Germany17 (17 nodes) and Géant (22 nodes). The physical supply networks and the corresponding TMs are available in [26], [43]. Moreover, each lightpath has capacity C equal to 40 Gbps.

TMs with granularity Δt equal to 15 minutes are available for Géant, while for Abilene and Germany17 TMs are measured every 5 minutes. In order to be consistent, we compute TMs with granularity 15 minutes for Abilene and Germany17 by taking the maximum values out of the 3 corresponding 5-minute TMs.

Total period covered by T_{past} (design of the SBN) equals 1 month for Abilene and Géant. Note that fine granular TMs (5 min.) cover only one day in the Germany17 network [43]. Therefore we use 12 TMs with time granularity equal to 1 month over the year 2004 to dimension the SBN. Since these TMs contain average values of traffic demands over a month, they alter temporal peaks of the traffic, and hence higher overprovisioning is needed during the design of the SBN.

We consider the total period covered by T_{fut} equal to 1 day. We select the evaluation days belonging to two different types (Working Day (WD) and WeekEnd day (WE)) in order to compare the MP-PA-LTD algorithms under various traffic conditions.

The original TMs from [43] are scaled in order to mimic actual traffic demands and to have comparable load in the three networks. We introduce the total demand per node $d_{|V|} = \sum_{(a,b)\in V\times V} d^{ab}_{SBN}/|V|$, and the corresponding unit Gigabit per second per node (Gpn). We consider three different load assumptions, and scale D_{SBN} to have the total demand per node equal to 100, 300 and 500 Gpn. The same scaling factors as for D_{SBN} are used for $D(t)$ for each $t \in T_{fut}$.

The networks, as well as the traffic data that we used for both the design of the SBN and evaluation of energy savings are summarized in Table I. Total demand (defined as $\sum_{(a,b)\in V\times V} d^{ab}(t)$) over time is indicated (as TRF) in Figures 4(a) and 5(a) for two exemplary days (2004-08-27 for Abilene and 2005-06-11 for Géant). We do not present all traffic patterns due to lack of space. More details can be found in [41].

B. Power and CapEx Data

Cisco CRS-1 router [44] was used to parameterize our study. Each LCS can accommodate up to W_{LCS} = 16 LCs, and a FCS can interconnect up to W_{FCS} = 9 LCSs. The power consumption values have been taken from [45]. In detail, a LCS consumes $\mathcal{P}^{LCS}$ = 2920 W and a FCS consumes $\mathcal{P}^{FCS}$ = 9100 W. We consider as LC the “Cisco CRS 4-port 10-GE Tunable WDMPHY Interface Module” with the “Cisco CRS-1 Modular Services Card”, consuming together $\mathcal{P}^{LC}$ = 500 W.

The CapEx values used during the design of the SBN have been taken from [46]. In particular, we adopt values of 13.37, 16.67 and 53.35 units to LC, LCS and FCS, respectively.

VI. Metrics

We describe the metrics adopted to assess the algorithms performance. We first introduce the power consumption of all active LCs in the network:

$$P^{LC}(t) = \mathcal{P}^{LC} \sum_{i\in V} x_i^{LC}(t) \tag{9}$$

The energy consumption due to LCs is then defined as:

$$E^{LC} = \sum_{t\in T_{fut}} P^{LC}(t)\Delta t \tag{10}$$

Moreover, we account also for the power of LCSs and FCSs. The number of LCSs used at each node is expressed as:

$$x_i^{LCS}(t) = \lceil x_i^{LC}(t)/W_{LCS} \rceil \tag{11}$$

Similarly, one FCS is used to interconnect up to W_{FCS} LCSs:

$$x_i^{FCS}(t) = \begin{cases} 0 & \text{if } x_i^{LCS}(t) \le 1 \\ \lceil x_i^{LCS}(t)/W_{FCS} \rceil & \text{otherwise} \end{cases} \tag{12}$$

We define the power consumption of active LCSs in the network as:

$$P^{LCS}(t) = \mathcal{P}^{LCS} \sum_{i\in V} x_i^{LCS}(t) \tag{13}$$

Similarly, the power consumption of active FCSs is defined as:

$$P^{FCS}(t) = \mathcal{P}^{FCS} \sum_{i\in V} x_i^{FCS}(t) \tag{14}$$

The total network energy consumption is hence defined as:

$$E^{TOT} = \sum_{t\in T_{fut}} \left[P^{LC}(t) + P^{LCS}(t) + P^{FCS}(t)\right]\Delta t \tag{15}$$

Together with energy consumption, we are also interested in assessing the performance of our algorithms in terms of

TABLE I
CONSIDERED NETWORKS AND TRAFFIC DATA [43]

Network	Nodes	Phy. supply links (bidir.)	TMs considered at SBN design (T_{past})	TMs to evaluate energy savings (T_{fut})
Abilene	12	15	max. between 2004-07-01 and 2004-07-31 (granularity of 5 min.)	every 15 min. over 2004-08-27 (WD), 2004-08-28 (WE), 2004-08-29 (WE), 2004-09-02 (WD)
Géant	22	36	max. between 2005-05-05 and 2005-06-04 (granularity of 15 min.)	every 15 min. over 2005-06-07 (WD), 2005-06-10 (WD), 2005-06-11 (WE), 2005-06-12 (WE)
Germany17	17	26	max. between 2004-01 and 2004-12 (granularity of 1 month)	every 15 min. over 2005-02-15 (WD)

reconfigured traffic. We therefore introduce the reconfiguration ratio[2] over all subsequent pairs of time periods in T_{fut} as:

$$\xi = \frac{\sum_{t\in T_{fut}} \sum_{i\in V} \sum_{j\in V} \sum_{a\in V} \sum_{b\in V} r_{ij}^{ab}(t)}{\sum_{t\in T_{fut}} \sum_{a\in V} \sum_{b\in V} d^{ab}(t)} \tag{16}$$

This metric captures the amount of traffic that is reconfigured over all time periods in T_{fut}, normalized by the total amount of traffic that is exchanged in the network. Note that the reconfigured traffic may be counted multiple times (as many times as many logical links a traffic demand passes from its source to its target), so ξ may be greater than 1.

Finally, we define the overload ratio metric ϕ to capture overload traffic in all periods $t \in T_{fut}$:

$$\phi = \frac{\sum_{t\in T_{fut}} \sum_{i\in V} \sum_{j\in V} \chi_{ij}(t)}{\sum_{t\in T_{fut}} \sum_{a\in V} \sum_{b\in V} d^{ab}(t)} \tag{17}$$

where $\chi_{ij}(t)$ is defined for each $t \in T_{fut}$, $i \in V$ and $j \in V$ as:

$$\chi_{ij}(t) = \max\left(\sum_{a\in V, b\in V} d^{ab}(t)\cdot f_{ij}^{ab}(t) - \sum_{l\in L_{(i,j)}} Cy_l(t), 0\right) \tag{18}$$

ϕ should be as low as possible (ideally 0) to prevent service disruptions and deterioration of QoS. Note that we account as overload each hop between a source and a target, even though the traffic may get dropped already at the first hop. Therefore, also ϕ may be greater than 1.

VII. RESULTS

We have implemented the algorithms presented in Section IV on custom simulators written in C++ and Java. The LFA and GA simulations are run on a server machine equipped with 2 Quad CPU at 2.66 GHz and 4 GB of RAM. The EWA simulations are run on a personal computer with a Dual Core CPU at 2.4 GHz and 2 GB of RAM. In particular, we start considering SBN with $d_{|V|} = 300$ Gpn of traffic and overprovisioning $\gamma = 0.5$. Unless specified otherwise, we adopt the following set of algorithm parameters: $\delta = 1.0$ for LFA, $\alpha = 0.1$, M = 500, S = 30 and K = 20 for GA, $W_L = 0.1$, $W_H = 0.9$ and $\psi = W_H$ for EWA. We first compare the algorithms with the following metrics: LCs daily energy consumption E^{LC}, total daily energy consumption E^{TOT}, reconfiguration ratio ξ, and overload ratio ϕ. Table II reports E^{LC} for the different scenarios, considering working and weekend days (WE label in the table). Focusing on the Abilene case, E^{LC} is lower for weekend days than working days since traffic is lower and hence more LCs are powered off. For example, considering the GA, E^{LC} is 821.75 kWh on 2004-09-02, and 689.5 kWh on 2004-08-29. Then, E^{LC} is higher for LFA: this is due to the fact that LFA switches off entire logical links rather than single lightpaths. However, turning off a logical link requires rerouting of the entire amount of traffic flowing on it, which is not always possible. This in turn leads to an increase of energy consumption, with E^{LC} always higher than 1645 kWh. On the contrary, both EWA and GA guarantee lower energy consumption, since they work on single lightpaths rather than logical links.

We then extend our analysis to the Germany17 and Géant networks. In particular, all the heuristics consume a larger amount of energy in Germany17 network than in Abilene. This is quite intuitive, since Germany17 has more nodes than Abilene. However, despite the Géant network being bigger than Germany17, the energy consumption on at least three out of four considered days in the Géant network is lower than in Germany17 on 2005-02-15. This can be explained by the traffic patterns on the days considered for evaluation of the heuristics, and by the overprovisioning of the SBNs. The overprovisioning of the Germany17 SBN is different from the overprovisioning of the other two networks despite using the same parameter γ. This is caused by the fact that the traffic data available for the Germany17 network contains only one day of TMs with fine granularity (see Section V-A and [43]). Therefore the TMs of granularity of one month were used to design the SBN (see Table I). Since the values in the TMs are average values over the considered period duration, the traffic peaks are averaged out, and are not included in D_{SBN}, which is calculated by taking maximum values for each demand over all TMs (see Eq. (8)). Interestingly, EWA and GA consume similar amount of energy in the Germany17 network compared to LFA suggesting that, for this network, it is difficult to turn off single lightpaths. This is caused by the fact that traffic in the Germany17 network is centralized in Frankfurt [26]. Only 9 out of 97 logical links not attached to Frankfurt in the SBN are composed of more than one lightpath. The LFA tries to switch off each logical link, however, since most of the links are composed of just a single lightpath, there is little difference to EWA and GA, which try to switch off single lightpaths, and not logical links. The (relatively little) advantage in terms of energy consumption that EWA and GA have over LFA in the Germany17 network is caused by the logical links attached to Frankfurt (21 out of 26 are composed of more than one lightpath), and the possibility of establishing logical links not existing in the SBN. Finally, we point out that EWA guarantees lower energy consumption E^{LC} with respect to GA and LFA in the Géant network (Table II).

In the following, we compare the heuristics considering the total energy consumption E^{TOT}. Table III reports the main results. In particular, E^{TOT} is higher than E^{LC}, since we are accounting also for the power of LCSs and FCSs.

[2] Note that $r_{ij}^{ab}(t)$ and ξ take no value in the first period of T_{fut}.

TABLE II
LINE CARD DAILY ENERGY CONSUMPTION E^{LC} [KWH]

Scenario	LFA	EWA	GA
2004-08-27 Abilene	2205.37	693.37	771.25
2004-08-28 Abilene (WE)	1673	587.75	697.875
2004-08-29 Abilene (WE)	1645.37	607.50	689.5
2004-09-02 Abilene	2255.62	712.75	821.75
2005-02-15 Germany17	2378.75	1946	1739
2005-06-07 Géant	3625.75	1312	1510.38
2005-06-10 Géant	2077	1231	1312.5
2005-06-11 Géant (WE)	2206.37	1136.12	1244.13
2005-06-12 Géant (WE)	2004.12	1061.5	1209.13

TABLE III
TOTAL DAILY ENERGY CONSUMPTION E^{TOT} [KWH]

Scenario	LFA	EWA	GA
2004-08-27 Abilene	4246.25	1534.33	1612.21
2004-08-28 Abilene (WE)	3385.65	1428.71	1538.84
2004-08-29 Abilene (WE)	3338.97	1448.46	1530.46
2004-09-02 Abilene	4330.29	1589.77	1683.75
2005-02-15 Germany17	5467.78	4729.9	4302.93
2005-06-07 Géant	7753.17	3391.11	3632.37
2005-06-10 Géant	4847.14	3246.36	3266.59
2005-06-11 Géant (WE)	5081.82	2997.75	3107.17
2005-06-12 Géant (WE)	4685.66	3024.23	3046.11

TABLE IV
RECONFIGURATION RATIO ξ

Scenario	LFA	EWA	GA
2004-08-27 Abilene	0.75	0.13	0.16
2004-08-28 Abilene (WE)	0.72	0.15	0.18
2004-08-29 Abilene (WE)	0.70	0.15	0.17
2004-09-02 Abilene	0.66	0.12	0.14
2005-02-15 Germany17	0.35	0.1	0.12
2005-06-07 Géant	0.40	0.09	0.11
2005-06-10 Géant	0.49	0.08	0.12
2005-06-11 Géant (WE)	0.48	0.1	0.13
2005-06-12 Géant (WE)	0.44	0.08	0.11

TABLE V
OVERLOAD RATIO ϕ

Scenario	LFA	EWA	GA
2004-08-27 Abilene	7×10^{-5}	0	0
2004-08-28 Abilene (WE)	0	0	0
2004-08-29 Abilene (WE)	3×10^{-5}	0	0
2004-09-02 Abilene	2×10^{-3}	0	0
2005-02-15 Germany17	5×10^{-3}	2×10^{-2}	4×10^{-6}
2005-06-07 Géant	8×10^{-4}	0	0
2005-06-10 Géant	0	0	0
2005-06-11 Géant (WE)	7×10^{-4}	0	0
2005-06-12 Géant (WE)	3×10^{-5}	3×10^{-5}	0

However, both GA and EWA are able to reduce the total energy consumption with respect to LFA, especially during weekends. These results confirm our intuition that minimizing the power consumption of LCs is of great benefit also for reducing the total power consumption of the network, assuming the possibility to switch off and on the LCSs and FCSs installed in the SBN.

As the next step, we compare the heuristics in terms of the reconfiguration ratio ξ. Table IV reports the results for the different scenarios. Intuitively, a ratio ξ approaching 1 indicates that the amount of reconfigured traffic is comparable with the total amount of traffic demands. This condition is not of benefit in a network, since it might have a negative impact on the QoS of users due to temporary service disruptions and network congestion as many devices are changing their operational state. Focusing on the Abilene network, ξ is typically larger than 0.66 for LFA. On the contrary, ξ is clearly reduced by the other heuristics, being lower than 0.15 and 0.18 for EWA and GA, respectively. This means that targeting explicitly the reconfiguration cost has a positive feedback on ξ. Similar considerations hold for the Germany17 and Géant networks. Finally, observe also that ξ does not significantly change over the different days, i.e., between working days and weekend days. This is due to the fact that a larger amount of traffic exchanged in the network (denominator of Eq. (16)) implies also a larger amount of reconfigured traffic (numerator of Eq. (16)).

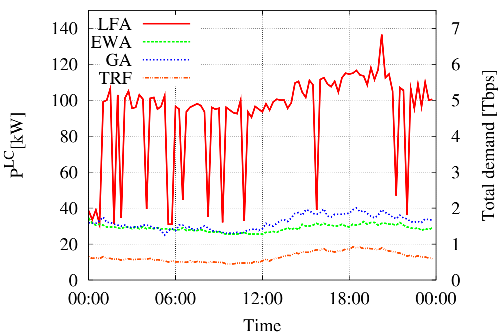
Finally, Table V reports the overload ratio over the different scenarios. Intuitively, ϕ should be kept as low as possible to limit the negative effects of packet dropping. Focusing on the Abilene network, $\phi = 0$ for both EWA and GA. On the contrary, $\phi > 0$ for different days when LFA is adopted. This is due to the intrinsic behavior of the algorithm: since LFA starts from SBN and tries to switch off logical links, in some cases the set of logical links provided by the SBN is not sufficient to satisfy the peak traffic.[3] Consequently, the overload is larger than zero, even if it is kept quite low, i.e., typically lower than 10^{-3}. On the contrary, both EWA and GA can accommodate the traffic demands more wisely, since they integrate the possibility to add lightpaths while satisfying the constraint of installed LCs in each network node. Table V reports also the results for the Germany17 network. In this case, $\phi > 0$ for all the heuristics, suggesting that the SBN is not sufficient to satisfy the traffic without exceeding the number of installed LCs. This is due to the fact that the SBN is designed with d_{SBN}^{ab} calculated using monthly averages of demand values (see Section V). Finally, the Table V reports the results for the Géant network. In this case, $\phi < 8 \times 10^{-4}$ and $\phi < 3 \times 10^{-5}$ for LFA and EWA, respectively. However, the overload is limited, since it occurs only in the first 15-minute period on 2005-06-12, and can be avoided by using the network configuration from the last period of 2005-06-11 instead of the SBN as a starting point. GA avoids overload for all the periods in the Géant network.

A. Time Variation

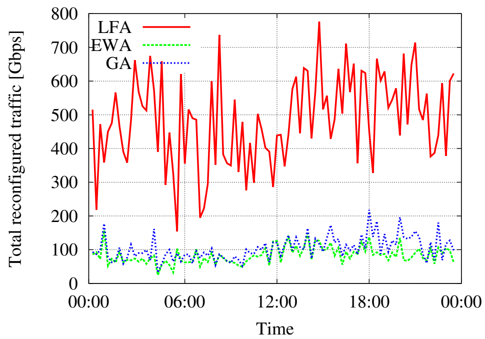
We then investigate the temporal behavior of the algorithms. In particular, we start considering the Abilene network[4] and the day 2004-08-27. Fig. 4(a) shows the power consumption of LCs versus time $P^{LC}(t)$. Power follows a day-night trend of traffic (right y-axis) for GA and EWA. Higher power is consumed by LFA, whose trend presents also spikes. In some cases LFA finds an aggressive configuration with many logical links switched off. Hence, the total power consumption is close to the other heuristics. However, the aggressive configuration is not able to accommodate traffic

[3] Recall that we have adopted different time periods for designing the SBN and for evaluating the heuristics.

[4] We do not change the time zone of the original TMs [43], therefore the day-night patterns in Abilene look shifted in time.

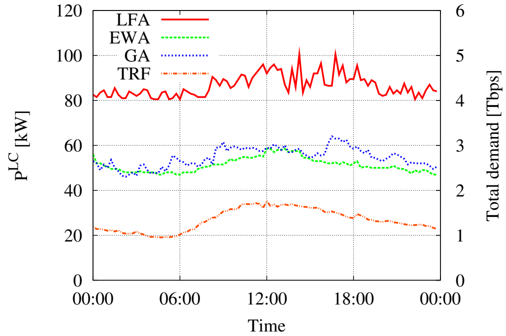


(a) Power consumption and total demand

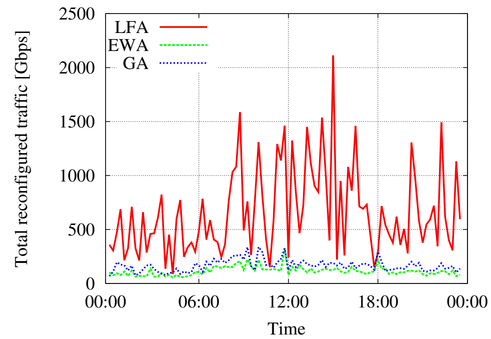


(b) Total reconfigured traffic

Fig. 4. Power consumption of active Line Cards, total demand and total reconfigured traffic in the Abilene network.



(a) Power consumption and total demand



(b) Total reconfigured traffic

Fig. 5. Power consumption of active Line Cards, total demand and total reconfigured traffic in the Géant network.

for a long period, i.e., more than one TM. This in turn leads to a new, less aggressive configuration of logical links with consistently higher power consumption. On the contrary, observe how GA and EWA are able to reduce power, with smooth power transitions. Note that the power consumption of all LCs installed in the SBN is more than 142 kW (not reported in the figure), thus we can conclude that our heuristics are effective in reducing the power consumption. To give more insight, Fig. 4(b) reports the total reconfigured traffic (sum of $r_{ij}^{ab}(t)$ in (1)), expressed in Gbps. Both GA and EWA reduce the amount of traffic that is reconfigured, so that the reconfigured traffic is always smaller than 220 Gbps. On the contrary, LFA always requires higher amount of reconfigured traffic.

We then extend our analysis considering the Géant network and the 2005-06-10 day. Fig. 5(a) reports power consumption of LCs versus time $P^{LC}(t)$. In this case, the power consumption of the always on network (SBN) is 276 kW, while our heuristics guarantee that power consumption is always lower than 105 kW. Again, a day-night behavior clearly emerges. Finally, the total reconfigured traffic is reported in Fig. 5(b). In this case, lower reconfigurations occur during the night for the three algorithms, suggesting that during the night the set of powered on devices does not frequently vary.

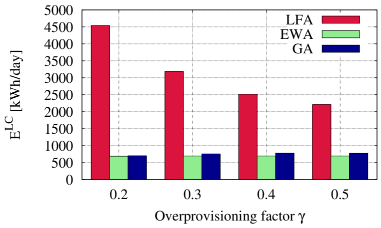
B. Impact of Static Base Network (SBN)

In this section, we investigate the impact of the SBN design on the performance of our heuristics. In particular, we vary the overprovisioning factor γ in the range [0.2-0.5], trading between large and medium overprovisioning of SBNs. Intuitively, large overprovisioning requires more capacity to be installed, implying more power consumption but also more freedom in choosing which devices to power off. We assume traffic per node $d_{|V|}$ equal to 300 Gpn, and focus on the days 2004-08-27 for Abilene, 2005-06-10 for Géant and 2005-02-15 for Germany17.

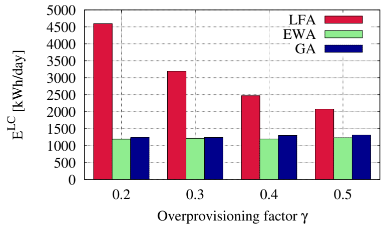
Fig. 6 reports E^{LC} and ξ for the different scenarios. γ impacts the performance of LFA. In particular, for the Abilene scenario E^{LC} of LFA passes from 2200 kWh with $\gamma = 0.5$ to more than 4500 kWh with $\gamma = 0.2$. The reason why energy consumed by LCs in a network using LFA increases with increasing overprovisioning of the SBN is that the logical links that LFA did not switch off are still overprovisioned proportionally to the overprovisioning of the SBN. On the contrary, when considering the reconfiguration ratio ξ, the variation of SBN does not impact consistently the results. Moreover, when considering the Germany17 network, all the algorithms consume a similar amount of energy for $\gamma = 0.5$ and $\gamma = 0.3$. This is due to the fact that, for this type of network, it is more difficult to turn off LCs due to different behavior of traffic used to design the SBN. Differently from LFA, both EWA and GA present just minor oscillations of energy consumption and reconfiguration ratio for all the values of γ. This is due to the fact that both algorithms are not restricted to logical links existing in the SBN, and that they consider establishment and release of single lightpaths, and not whole logical links.

C. Impact of Load Variation

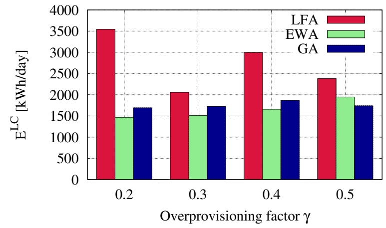
Keeping the day-night traffic variation, we vary the total traffic per node $d_{|V|}$ between 100 Gpn and 500 Gpn in the SBN design phase with γ set to 0.5. We consider the day 2004-08-27 for Abilene, and the day 2005-06-10 for Géant.



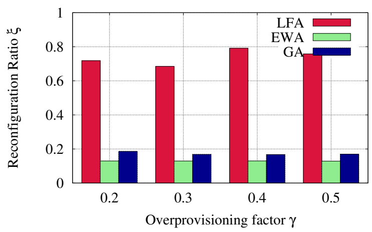
(a) E^{LC} for Abilene



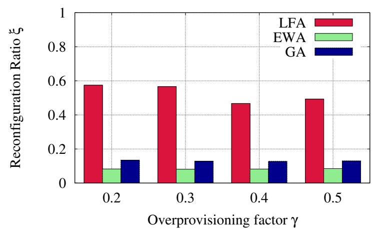
(b) E^{LC} for Géant



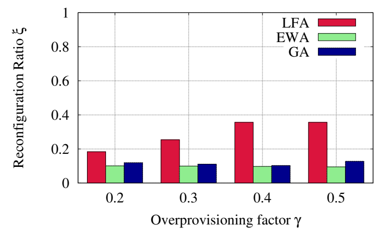
(c) E^{LC} for Germany17



(d) ξ for Abilene

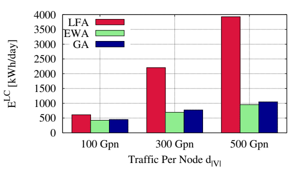


(e) ξ for Géant

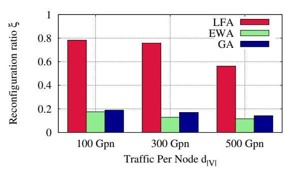


(f) ξ for Germany17

Fig. 6. SBN Variation: Energy consumption and reconfiguration ratio in the Abilene and Géant networks.

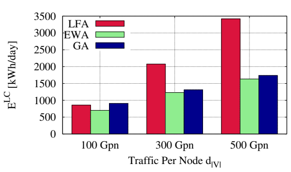


(a) Energy Consumption

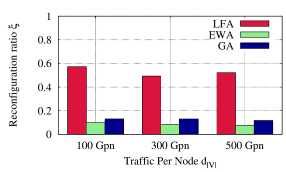


(b) Reconfiguration Ratio

Fig. 7. Load Variation: Energy consumption and reconfiguration ratio in the Abilene network.



(a) Energy Consumption



(b) Reconfiguration Ratio

Fig. 8. Load Variation: Energy consumption and reconfiguration ratio in the Géant network.

Fig. 7 reports the results for the Abilene network. E^{LC} is increasing with $d_{|V|}$ for all the algorithms (as expected). Interestingly, all the algorithms consume a similar amount of energy for $d_{|V|} = 100$ Gpn, since under little load a minimum number of LCs has to be always powered on to guarantee connectivity. However, as traffic increases, the LFA consumes more energy than GA and EWA. Moreover, ξ decreases as $d_{|V|}$ increases for EWA and GA, suggesting that these algorithms can wisely accommodate the increase of traffic by limiting the amount of reconfigurations.

Similar considerations hold also for the Géant network, reported in Fig. 8. It is interesting to note that the GA consumes slightly more energy than LFA under low load ($d_{|V|} = 100$ Gpn).

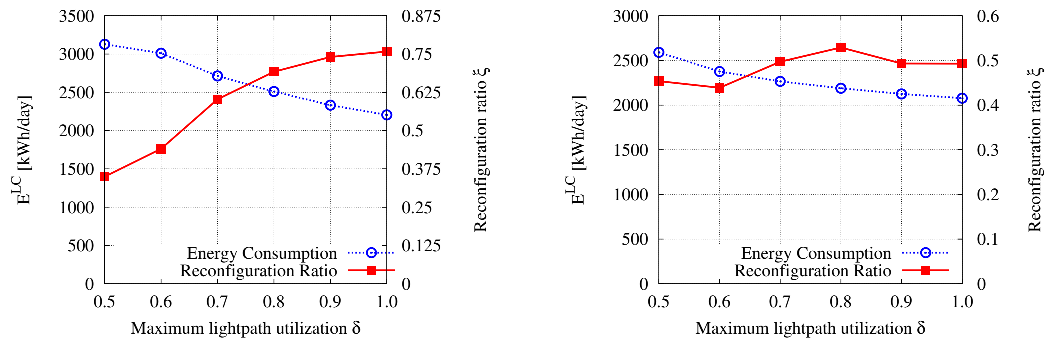
D. Sensitivity Analysis

In this section we evaluate the impact of the algorithm parameters on E^{LC} and ξ. We adopt the following scenarios: the day 2004-08-27 for Abilene, and the day 2005-06-10 for Géant. We set $\gamma = 0.5$ and $d_{|V|} = 300$ Gpn.

We first consider the LFA algorithm over the Abilene scenario. In particular, we vary the maximum logical link utilization δ. Fig. 9(a) reports E^{LC} and ξ for $\delta = [0.5, 1.0]$. The energy consumption decreases as δ increases. This is due to the fact that, as δ approaches 1, it is easier to shift traffic to unused logical links and consequently save energy. However, this is not beneficial for the reconfiguration ratio, with ξ passing from 0.37 with $\delta = 0.5$ to 0.75 with $\delta = 1.0$, suggesting that the algorithm is too aggressive in selecting the set of devices to be powered off. Fig. 9(b) reports the results for the Géant network. Also here the energy is minimized for $\delta = 1.0$, while ξ ranges between 0.45 and 0.52.

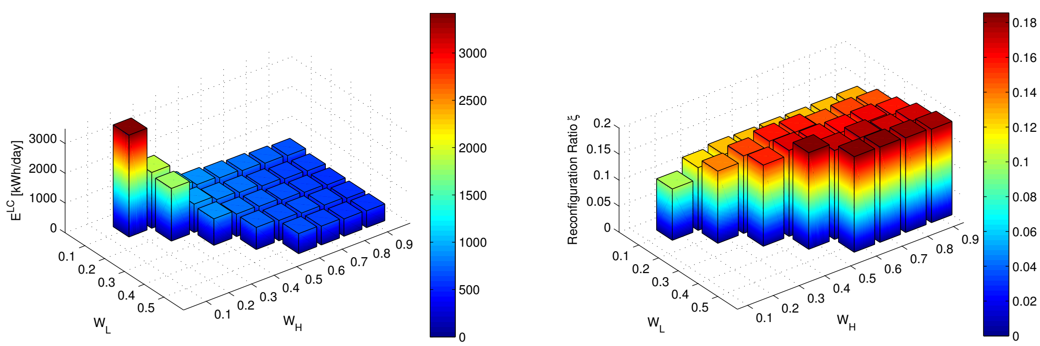
We then consider the EWA algorithm. We vary both the low threshold W_L and the high threshold W_H. E^{LC} and ξ for the Abilene network are reported in Fig. 10(a) and Fig. 10(b), respectively. Interestingly, the energy consumption steadily increases for $W_L \leq 0.3$ and $W_H \leq 0.3$, while the reconfiguration ratio is minimized. This is due to the fact that with this setting the algorithm tries to switch off lightpaths (low W_L) less frequently, but many devices are required to be powered on (overprovisioning due to low W_H). Conversely, with increasing values of watermarks ($W_L > 0.3$ and $W_H > 0.4$) the energy consumption decreases, but the reconfiguration ratio increases. Intuitively, for high values of W_L the algorithm is more aggressive in switching off devices, while for high W_H the algorithm tends to save more power since lightpath utilization increases. However, a good trade-off is guaranteed by setting $W_L = 0.1$ and $W_H > 0.4$. Fig. 11 reports the results for the Géant network. Also here the energy is clearly minimized for high values of W_L and W_H (conversely for the reconfiguration ratio). A good trade-off in this case is to set $W_L = 0.1$ and $W_H = 0.9$.

Finally, we have performed a sensitivity analysis on the GA algorithm. In particular, we have varied α, which weighs differently the reconfiguration costs with respect to power consumption. Similarly to $\mathcal{R}$ introduced in Section III-B, the parameter α allows to trade between the power consumption and the reconfigured traffic when searching for the optimal solution. Thus, α should be set according to the importance given to the two metrics. Fig. 12(a) reports E^{LC} and ξ for the Abilene scenario. Astonishingly, ξ passes from more than 0.9 with $\alpha = 0.9$ to less than 0.14 with $\alpha = 0.1$, suggesting that the reconfiguration cost steadily increases when power consumption becomes the predominant term in the utility



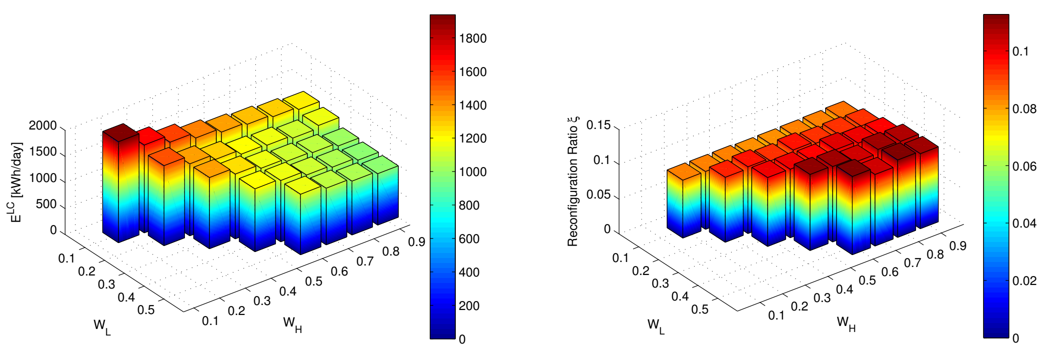
(a) Abilene (b) Géant

Fig. 9. LFA Sensitivity Analysis for the Abilene and Géant networks.



(a) Energy Consumption (b) Reconfiguration Ratio

Fig. 10. EWA Sensitivity Analysis for the Abilene network.



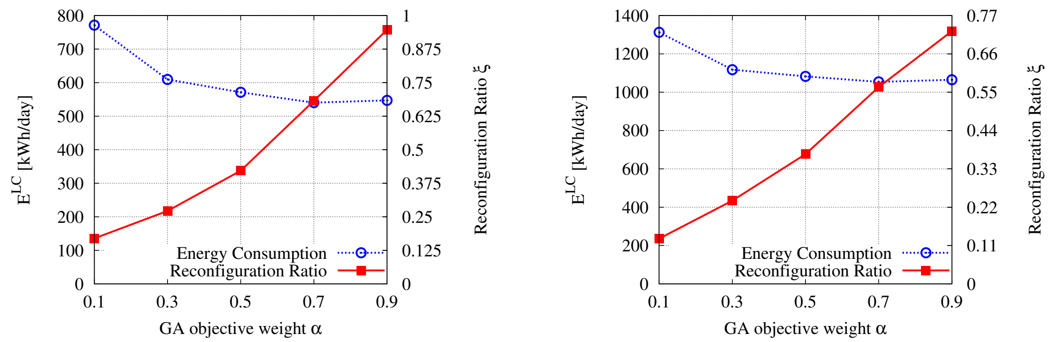
(a) Energy Consumption (b) Reconfiguration Ratio

Fig. 11. EWA Sensitivity Analysis for the Géant network.

function. On the other hand, E^{LC} increases as α decreases and reaches an asymptote of about 540 kWh/day. To give more insight, we have performed the sensitivity analysis also for the Géant network, reported in Fig. 12(b). Again, observe how much the choice of α is critical to trade between the reconfiguration costs and energy consumption. The obtained results suggest then that it may be better to choose a low value for α, since, in that case, the reconfigured traffic is effectively minimized, while the power consumption of the network is not affected too much.

E. Power Breakdown

We then investigate how much energy is consumed by components of each type, differentiating between LCs, LCSs, and FCSs. In particular, the minimization of power due to LCs is targeted by the heuristics, while the power due to LCSs and FCSs is computed in a postprocessing phase. Fig. 13 on the top reports the power consumption versus time for the Abilene over 2004-08-27. The LFA heuristic (Fig. 13(a)) requires all types of components to be powered on over the whole day, with a large amount of power consumed by LCs during the day. The EWA heuristic (Fig. 13(b)) instead does not require any FCS, and a lower amount of power is consumed by LCs compared to LFA. Moreover, the power



(a) Abilene (b) Géant

Fig. 12. GA Sensitivity Analysis for the Abilene and Géant networks.

TABLE VI
COMPUTATION TIMES [S]

Scenario	Statistic	LFA	EWA	GA
2004-08-27 Abilene	median	0.84	0.01	25.8
	average	0.85	0.03	26
	maximum	0.92	1.75	31
2005-06-10 Géant	median	0.89	0.13	147.57
	average	0.89	0.31	144
	maximum	0.98	15.06	225
2005-02-15 Germany17	median	0.86	0.35	63.43
	average	0.87	0.49	48
	maximum	0.95	5.85	156

consumed by LCSs is constant, suggesting that EWA is able to find a stable solution for this type of devices. Finally, the power variation of GA, reported in Fig. 13(c) is similar to EWA, with higher variation of power consumed by LCs.

We then consider the Géant network over 2005-06-10 (the second row in Fig. 13). Interestingly, all the algorithms require to use FCSs. This is due to the fact that in this case, differently from Abilene, the distribution of traffic imposes to use more hops on average, and some nodes route a large amount of traffic. Moreover, both LCs and FCSs present a day-night trend, while the power consumption of LCSs is almost constant. This is however influenced by significantly higher power consumption of an FCS than the power of a LCS (9100 W and 2920 W according to Section V-B), and significantly higher number of installed LCs than LCSs.

F. Computation Times and Complexity

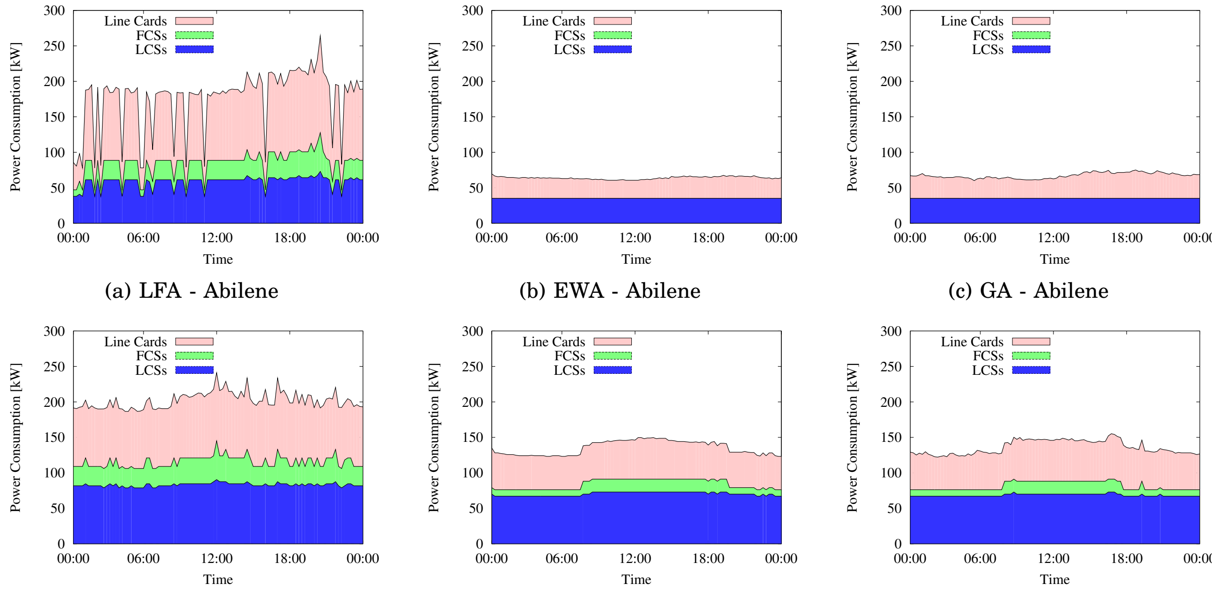
Table VI reports the comparison of the computation times required by the algorithms. EWA was simulated on a slower computer than LFA and GA, therefore the results in Table VI should be treated just as indicative ones.

LFA and EWA require the lowest amount of time to compute a solution. While the average computation times are close to median for LFA, EWA needs more time in the first period when switching off many lightpaths from the SBN. The adaptive behavior of EWA results in lower computation times in the next periods, which is reflected by different average and median computation values. GA requires more time than LFA and EWA, since several iterations are required to return the solution.

Focusing on computational complexity, the LFA first requires a sorting of the set of logical links, resulting in a time $\mathcal{O}\left(|L|\log|L|\right)$. Then, the computation of the paths and the constraints checks, which correspond to the flow conservation of the traffic demands and to the bandwidth utilization of the logical links (the constraints (2) and (4) of the MILP), can be done in time $\mathcal{O}\left(|V|^2\right)$. The procedure has to be repeated over the set of links, resulting in $\mathcal{O}\left(|L|\cdot|V|^2\right)$. Thus, the total algorithm complexity is $\mathcal{O}\left(|L|\log|L|+|L|\cdot|V|^2\right)$.

The computational complexity of GA is mainly dependent on the size of the network. Indeed, the complexity of the operations concerning the evolutionary process is dependent on the size of an individual which is equal to $|V|^2$. Thus, their complexity is $\mathcal{O}\left(|V|^2\right)$. In addition, the complexity for the operations of constraints checks, which are the same of LFA plus the check of the number of installed LCs in the SBN (the constraints (7) of the MILP), is also equal to $\mathcal{O}\left(|V|^2\right)$. These operations have to be repeated over all the individuals in the worst case, resulting in a complexity of $\mathcal{O}\left(S\cdot|V|^2\right)$. Moreover, the complexity of the GA depends also on the size of the offspring K and the maximum number of generations without improvement of the fitness function M. In particular, the total complexity is equal to $\mathcal{O}\left(M\cdot K\cdot S\cdot|V|^2\right)$. Both M, K and S constrain the search space of the GA. Consequently, these parameters determine the convergence time and the quality of the results. For instance, for low M, the amount of time employed by the GA is low, but it is likely to have worse result at the end, since few iterations are performed. Similarly, if a large number of individuals is generated at each generation, more solutions are examined and, thus, the search space increases together with the convergence time. In this work, we keep M, K and S fixed for all the simulations and we choose to use values that allow to find better solutions, at the cost of a larger execution time of the heuristic.

Finally, complexity of EWA is dependent on the input parameters, in particular on the network configuration in the previous time period. The IP routing of traffic demands $f_{ij}^{ab}(t-1)$ together with the current TM $D(t)$ influence the logical links where the utilization of the last lightpath violates the watermarks W_L and W_H. This in turn influences the attempts to establish and release lightpaths. The lightpath establishment is also dependent on the number of installed LCs in the SBN X_i^{LC}, and the number of established lightpaths forming logical links $y_l(t-1)$ influences the number of attempts to release lightpaths. We perform the worst-case complexity assessment of EWA assuming first that no demand is routable at the beginning of the algorithm, next that watermarks are violated on all logical links, and eventually that a new lightpath between each pair of LCs can be established.



(a) LFA - Abilene (b) EWA - Abilene (c) GA - Abilene

(d) LFA - Géant (e) EWA - Géant (f) GA - Géant

Fig. 13. Power Breakdown for the Abilene and Géant networks.

We assess each step of the EWA presented in Alg. 3. Ensuring routability of demands over the network requires time $\mathcal{O}\left(|V|^2 \cdot |V|^2 \log |V|\right)$, since there are up to $|V \times V|$ traffic demands, and establishing of a new logical link for any demand may influence the routability of all demands, which need to be sorted ($|V|^2 \log |V|$). Sorting of the logical links according to the utilization of the last lightpath takes $\mathcal{O}\left(|L| \log |L|\right)$. Establishing of necessary lightpaths requires three types of operations: i) iterations over all the logical links where the high watermark W_H is exceeded ($|L|$), ii) sorting of the demands flowing through the logical link ($|V|^2 \log |V|$), iii) possible iterations over all demands flowing through the logical link ($|V|^2$). Finally the whole procedure has to be repeated in case a new lightpath is established between any LCs with the total number of LCs installed in the network defined as $R = \sum_{i \in V} X_i^{LC}$. The overall complexity of establishing of the necessary lightpaths (consisting of the above three types of operations) is $\mathcal{O}\left(|L| \cdot \left(|V|^2 \log(|V|) + |V|^2\right) \cdot R^2\right)$ (see [41]). Releasing unnecessary lightpaths takes $\mathcal{O}\left(G \cdot |L| \log |L|\right)$, where $G = \sum_{l \in L} y_l(t-1)$ denotes the number of established lightpaths in the previous time period, and $|L| \log |L|$ accounts for the fact that releasing each single lightpath forces sorting of logical links. The overall complexity of EWA (Alg. 3) can be therefore estimated in the worst case as $\mathcal{O}\left(|V|^4 \log |V| + |L| R^2 |V|^2 \log |V| + G |L| \log |L|\right)$.

In conclusion, all algorithms present complexity that scales at least as $|V|^2$. Moreover, complexity of both GA and EWA depends on the input parameters, which can be used to trade between quality of results and computation time. Finally, complexity of LFA is independent from the input parameters, and it is fixed given the SBN.

G. Monetary Savings

Finally, we have estimated the impact of our heuristics on the monetary cost needed to power the network. In particular, we have selected the day 2004-08-27 for Abilene, the day 2005-06-10 for Géant, and the day 2005-02-15 for Germany17. By assuming that the same daily traffic profile is repeated over the whole year we have computed the total energy consumed by the network in a year, and the corresponding electricity costs.[5] A cost of 0.0936 € per kWh is assumed, based on current statistics of electricity prices in Europe [47]. Table VII reports the costs for the three algorithms. Although not being the main focus of this paper, percentage savings with respect to an always on solution are reported in the parenthesis. Considering the Abilene network, an always on solution requires 280000 € per year. With LFA this amount can be almost halved, while with EWA and GA savings larger than 80% can be achieved, with 52000 € required to run the network with EWA. Higher savings can be achieved for the Géant network, with the lowest amount of electricity required by the EWA algorithm. Finally, savings between 28% and 43% are achieved with the Germany17 network. These results corroborate our intuition that reducing power consumption is of significant benefit also for reducing the associated monetary cost.

TABLE VII
YEARLY MONETARY COST [K€]

	Abilene	Géant	Germany17
ALL ON	280	526	260
LFA	145 (-48%)	166 (-69%)	186 (-28%)
EWA	52 (-81%)	110 (-79%)	161 (-38%)
GA	55 (-80%)	112 (-79%)	147 (-43%)

VIII. Discussion and Implementation Issues

Power savings and amount of reconfigured traffic depend on the traffic variation over time. We varied the load in Section VII-C, but the rate of traffic changes plays also an important role. The algorithms (especially EWA) are designed for typical day-night traffic variation in a backbone network. Traffic in this kind of networks is smooth due to aggregation of hundreds of end-to-end flows. Extraordinary and large peaks of traffic are unlikely, and caused by e.g.,

[5] Weekend days may further decrease the electricity consumption.

natural disasters or terrorist attacks, but also transmission of multiple grid jobs. They may reduce the opportunity for putting devices into sleep mode, and in such cases, we expect lower power savings with a higher amount of reconfigured traffic. Besides, these situations may also result in network overload if the devices that were put into sleep mode cannot be awakened fast enough, or if the network is improperly dimensioned. Lastly, the algorithms may fail to find a suitable network configuration for supporting these peaks of traffic, which may impair the network availability. These issues and the exact domain of validity of the algorithms with respect to traffic dynamics have not been studied in this paper, and are left for future work.

In our case, we have evaluated our heuristics over two weekend days and two working days (for the Géant and Abilene networks), and one day for the Germany17 network. We have selected these days, because of their typical day-night traffic variation in a backbone network. We assume that in normal conditions, traffic in the network varies with a similar trend, and so the power saving and the amount of reconfigured traffic would be similar. Moreover, the adopted time granularity (one TM every 15 minutes) is sufficient to mimic the real traffic variation in the network.

Furthermore, there are different implementation issues that need to be taken into account when introducing the proposed heuristics into the networks. First of all, the feature of remote activation and deactivation of the LCs, and potentially also LCSs and FCSs has to be integrated into IP routers. Although commercial routers available today do not posses this functionality yet, their vendors work on its implementation [48]. In general, estimating the time that is needed to power up a LC in an IP-over-WDM network is not trivial. However, the 3 microseconds needed to wake up a 10 Gbps link in the emerging 802.3az standard [27] makes us believe that the wake-up process will be quick enough to follow the traffic variation.

Additionally, in the case of a centralized controller, it is necessary to consider the time needed to run the algorithm (the approximate time is indicated in Table VI, considering that the algorithms' implementation is not explicitly optimized to be time effective) and the time to disclose the new network configuration to all the nodes. This can be done using a new signaling mechanism or an already existing one. For instance, the computed network configuration can be put inside LSA packets, assuming the existing MPLS as the control plane [30]. Alternatively, the algorithms can be run in a distributed manner at each node, which requires prior collection of the necessary global data.

Lastly, additional time is needed to reconfigure the network, first switching on new equipment, then making sure that all the traffic has been rerouted, and eventually switching off idle equipment. The make-before-break mechanism [49] can be used for this purpose.

IX. Conclusion

We have targeted the reduction of power consumption in IP-over-WDM networks, by selectively turning off LCs during periods of low traffic. In particular, we have first formulated the Multi-Period Power-Aware Logical Topology Design problem (MP-PA-LTD) as an optimization problem. Then, we have proposed three different heuristics to solve the MP-PA-LTD, namely LFA, GA and EWA. The LFA targets the minimization of the number of logical links in the network, while both GA and EWA work on single lightpaths. Differently from the previous work, we take into account the amount of traffic which is reconfigured in the network.

We have evaluated our algorithms over a wide set of network scenarios taking as realistic parameters as possible. Our results indicate that switching off LCs is of great benefit to reduce the power consumption of the network. Moreover, both GA and EWA are able to wisely trade between power and reconfigured traffic, and this trade-off can be controlled by a proper setting of the input parameters. Then, we have shown that with our heuristics the traffic load impacts the power consumption, but only marginally the associated reconfiguration ratio. Additionally, also the overprovisioning of the SBN has a limited impact on the reconfiguration ratio. Finally, we have shown that reducing power consumption is of significant benefit for reducing the associated monetary cost.

In conclusion, our results indicate that large savings are possible while keeping the reconfigured traffic low. This is true especially for the GA and EWA algorithms, which are designed to switch off single lightpaths rather than full logical links. Moreover, the average computation time below 0.5 s (median below 0.35 s) makes the EWA a candidate to be implemented in operational core networks.

Acknowledgment

This paper is dedicated to the memory of prof. Fabio Neri, who suddenly passed away in April 2011. Fabio was a full professor at Politecnico di Torino, and his suggestions on optical networks helped us in the initial steps of this work.

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APPENDIX A
SUMMARY OF THE NOTATION

Table VIII contains explanation of all the symbols used in this work.

TABLE VIII
NOTATION USED IN THE MILP, LFA, GA, EWA AND METRICS

		Symbol	Description
Parameters	General and MILP	$H = (V, L)$	directed logical supply network with nodes V and supplied logical links L
		$L_{(i,j)}$	supplied logical links between nodes i and j, $\lvert L_{(i,j)}\rvert = 1$ for each $(i, j) \in V \times V$
		C	capacity (bitrate) of a lightpath
		δ	maximum lightpath utilization, $\delta \in (0, 1]$
		$\mathcal{R}$	cost associated with each unit of reconfigured traffic
		$\mathcal{P}^{LC}$	power consumption of a Line Card (LC)
		$\mathcal{P}^{LCS}$	power consumption of a Line Card Shelf (LCS)
		$\mathcal{P}^{FCS}$	power consumption of a Fabric Card Shelf (FCS)
		W_{LCS}	number of LCs that can be accommodated by a LCS
		W_{FCS}	number of LCSs that can be accommodated by a FCS
		T_{past}	set of considered past (known) time periods
		T_{fut}	set of considered future (unknown) time periods
		T	set of all considered time periods, $T = T_{past} \cup T_{fut}$, $T_{past} \cap T_{fut} = \varnothing$
		Δt	duration of each time period $t \in T_{fut}$
		$D(t)$	a Traffic Matrix (TM) for time period $t \in T$
		$d^{ab}(t)$	element of $D(t)$, value of traffic demand between nodes $(a, b) \in V \times V$
	SBN design	D_{SBN}	TM used to design the SBN
		d^{ab}_{SBN}	element of D_{SBN}, value of traffic demand between nodes $(a, b) \in V \times V$ (maximum over T_{past}, Eq. (8))
		$d_{\lvert V\rvert}$	total demand per node (in Gbps per node)
		γ	overprovisioning factor defined as the ratio between the lightpath's capacity used during the SBN design and its full capacity, $\gamma \in (0, 1]$
		X^{LC}_i	number of installed LCs in each node $i \in V$ of the SBN (solution values)
		Y^{SBN}_l	the set of logical links from the SBN (solution values)
	Heuristics	α	weight of the GA's objective, $\alpha \in [0, 1]$
		M	maximum number of generations without improvements (GA) , $M \in \mathbb{Z}_+$
		S	population size (GA), $S \in \mathbb{Z}_+$
		K	offspring size (GA), $K \in \mathbb{Z}_+$
		W_L	a threshold on the utilization of the last lightpath on a logical link to trigger attempts to release lightpath(s) (EWA), $W_L \in [0, 1)$
		W_H	a threshold on the utilization of the last lightpath on a logical link to trigger attempts to establish additional lightpath(s) (EWA), $W_H \in (0, 1]$
		ψ	maximum utilization of last lightpath on a logical link (EWA), $\psi \in (0, 1]$
Variables		$f^{ab}_{ij}(t)$	whether the traffic demand originated at node $a \in V$ and targeted to node $b \in V$ traverses the logical link from $i \in V$ to $j \in V$ in time period $t \in T_{fut}$, $f^{ab}_{ij}(t) \in \{0, 1\}$
		$r^{ab}_{ij}(t)$	amount of reconfigured traffic (in Gbps) between nodes a and b on the logical link from $i \in V$ to $j \in V$ in time period $t \in T_{fut}$, $r^{ab}_{ij}(t) \in \mathbb{R}_+$
		$y_l(t)$	number of lightpaths established on the logical link l in time period $t \in T_{fut}$, $y_l(t) \in \mathbb{Z}_+$
		$x^{LC}_i(t)$	number of LCs powered on at each node $i \in V$ in time period $t \in T_{fut}$, $x^{LC}_i(t) \in \mathbb{Z}_+$
Metrics		$x^{LCS}_i(t)$	number of LCSs used at each node $i \in V$ in time period $t \in T_{fut}$, Eq. (11)
		$x^{FCS}_i(t)$	number of FCSs used at each node $i \in V$ in time period $t \in T_{fut}$, Eq. (12)
		$P^{LC}(t)$	power consumption of all active LCs in time period $t \in T_{fut}$, Eq. (9)
		$P^{LCS}(t)$	power consumption of all active LCSs in time period $t \in T_{fut}$, Eq. (13)
		$P^{FCS}(t)$	power consumption of all active FCSs in time period $t \in T_{fut}$, Eq. (14)
		E^{LC}	energy consumption due to LCs over T_{fut}, Eq. (10)
		E^{TOT}	total network energy consumption (due to LCs, LCSs and FCSs) over T_{fut}, Eq. (15)
		ξ	reconfiguration ratio over T_{fut}, Eq. (16)
		ϕ	overload ratio over T_{fut}, Eq. (17)
		R	total number of LCs installed in the network
		G	number of established lightpaths in the previous time period