Overview and outlook on Energy-Aware Adaptive Routing Solutions in IP-over-WDM networks

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***Abstract*—Today's core networks are permanently powered on and consume non-negligible amounts of energy. Traffic varies over time giving opportunities to switch off or put into standby mode a subset of network devices in order to save energy in low-demand hours. We take a broad view on energy saving in Internet Protocol (IP)-over-Wavelength Division Multiplexing (WDM) networks looking at (1) potential savings, (2) savings considering limited computation time of network configuration as well as reconfiguration costs, and (3) implementability issues (including verification of the proposed solutions on an IP-over-Gigabit Ethernet (GbE) testbed). Particular care is taken for choosing input parameters for our studies. Eventually, we outline the open issues that are currently under investigation.**

I. Introduction

Information and Communication Technologies (ICTs) are changing our lives. They often make our lives easier, but have some drawbacks. Energy consumption is one of the aspects that has to be taken into account when developing newer and newer ICTs. The ICTs undoubtedly allow us to save fuel needed to commute if there were no Internet banking, online shops, etc., however the increasing amount of information that is exchanged via the Internet enforces increase of energy consumed by the ICTs [2]. Therefore many efforts are currently put into reduction of energy consumed by ICTs [3].

This work focuses on IP-over-WDM core networks. WDM lightpaths provide high capacity links between IP routers. The IP routers aggregate traffic originating from access and metro networks. The aggregated traffic varies over time. The diurnal traffic variations offer possibilities to switch some devices off in low demand hours in order to save energy. We ask the following questions: (1) what is the potential of energy saving in the IP-over-WDM networks? (2) how high are the energy savings taking into account reconfiguration costs and limited time for dynamic computation of network configuration? (3) is it feasible to introduce energy saving techniques into operational networks? As realistic input data as possible is used for the evaluation studies.

This paper provides an overview of the thesis [1] (and corresponding publications) showing its main results and thus giving a big picture of the energy saving in IP-over-WDM networks using Energy-Aware Adaptive Routing Solutions (EA-ARSs) and sleep modes. Extensive overview of the related work is provided in [1] and skipped here due to space constraints. Mixed-Integer Linear Programming (MILP), simulations and experiments on a testbed are performed to find answers to the questions listed above.

This is a summary of the PhD thesis awarded with the KuVS Prize 2015 for the best PhD Thesis / Dissertation. The PhD Thesis [1] was completed at Technische Universität Berlin, TKN, Berlin, Germany under the supervision of Prof. Dr.-Ing. Adam Wolisz. The work on this article as well as the current work outlined in the final section of this article is supported by the Polish National Science Center (decision DEC-2014/12/S/ST7/00415). We acknowledge all the co-authors of the publications related to [1].

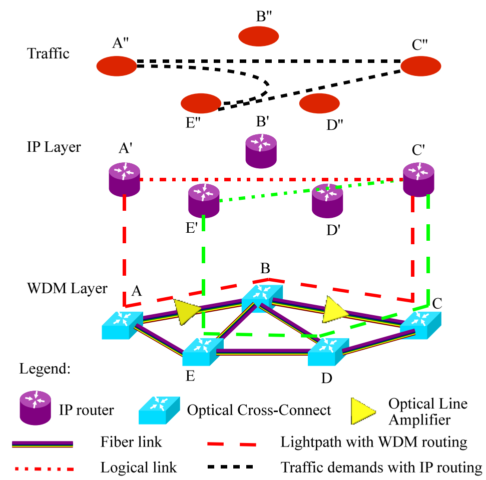


Fig. 1. Model of the considered IP-over-WDM network in an exemplary configuration. Colors of lightpaths determine wavelengths used by the lightpaths.

The paper is organized as follows. We present the network model and scenarios (topologies, traffic data, power values, testbed description) in Section II. Methodology is discussed in Section III. Section IV contains results. Finally, Section V concludes our work and outlines current and future work.

II. Network model and scenarios

We present the network model first. Network scenarios are presented next.

A. IP-over-WDM network

A model of the IP-over-WDM network in an exemplary configuration is presented in Fig. 1. It consists of two layers, i.e., the WDM layer and the IP layer. Optical Cross-Connects (OXCs) interconnected by fiber links form a physical topology in the WDM layer. A fiber link consists of one or more fibers. The physical supply topology (in contrast to the physical topology) determines the nodes and links where network devices and fibers can be installed at the network design stage. A fiber can carry up to B multiplexed optical signals (notation is summarized in the appendix of [1]). The optical signal traversing a fiber needs to be amplified every R kms by Optical Line Amplifiers (OLAs).

An optical WDM channel originating and terminating in the transponders and traversing two or more OXCs is called a lightpath. A lightpath may span multiple fiber links and has capacity W bps. Each intermediate node traversed by the lightpath essentially provides an optical bypass facility [4]. The lightpath can be assigned a unique wavelength on all physical links that it traverses or wavelength converters can be used at intermediate nodes. Each wavelength can be used only once at each fiber.

IP routers interconnected by logical links form a logical topology. A logical (IP) link consists of all parallel lightpaths (regardless of their realization in the WDM layer) between a pair of IP routers. The IP routers correspond to logical nodes. Lightpaths are transparent to the IP routers.

A router model from [5] is used in this work. One port card corresponding to each slot card is assumed. A slot card equipped with a port card forms a line card. We use colored line cards, since they are more energy-efficient than gray line cards combined with transponders.

Looking at both the IP and WDM layers, line cards and OLAs respectively are the devices that are particularly targeted for switching off in the low-demand hours in the literature. The IP routers cannot usually be switched off because of the constantly present traffic originated from or targeted to them. The same way of reasoning makes switching off the whole OXCs difficult. Thanks to the modular structure of the IP routers, their parts (i.e., Line Card Shelves (LCSs) and Fabric Card Shelves (FCSs) [6]) could be switched off. However, their boot times are expected to be much higher than the times needed to activate and deactivate line cards. Dynamic operation of OLAs is more difficult than dynamic operation of line cards due to transient (thermal) effect of optical transmission [7]. Therefore line cards are targeted to be switched off in this work.

Source-target traffic demands (stored in a traffic matrix $D(t)$ for time t) arrive at the IP routers from lower hierarchy networks. The traffic has to be routed through the logical topology in order to get from its source node to its target node. Similarly, lightpaths have to be routed through the physical topology in order to provide connectivity between the IP routers. Introducing flexibility of routing into one or both layers increases the complexity of the network operation, but offers potential of energy saving.

Taking a broad view on the implementation of energy saving using EA-ARSs we can distinguish the following mandatory actions (as shown in Fig. 2): (1) traffic monitoring; (2) validation of events triggering network reconfiguration; (3) calculation of the energy-efficient network configuration; (4) network reconfiguration. The main focus of [1] is on proper calculation of network configuration with realistic input traffic data. The proposed calculation methods contain load thresholds. Their violations can be used as triggering events. Traffic monitoring and network reconfiguration is discussed and validated using testbed experiments in this work.

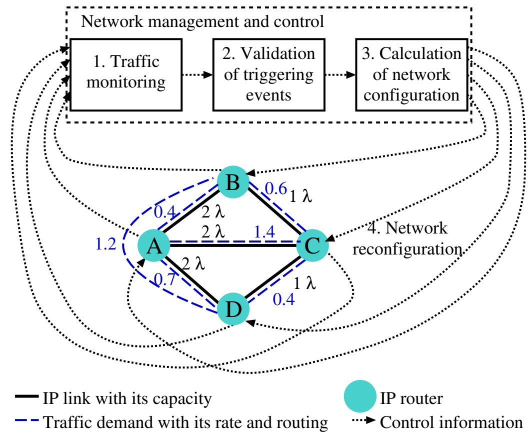


Fig. 2. Steps needed for energy saving (traffic rates in Gbps, IP link capacities in number of lightpaths denoted as λ in the figure).

TABLE I
TRAFFIC AND PHYSICAL SUPPLY TOPOLOGIES [8].

Name	Nodes	Links	Time granularity	Time horizon	No. of traffic matrices
Abilene	12	15	5 min	6 months	48096
Germany17	17	26	5 min	1 day	288
(Nobel-			1 day	1 month	28
Germany [8])			1 month	1 year	14
Géant	22	36	15 min	4 months	11460

B. Network scenarios

Realistic input parameters have to be carefully chosen in order to properly estimate energy saving. The input parameters particularly relate to traffic data and power consumption data, which are critical for energy saving.

Traffic and topologies Extensive search of realistic input data was performed within [1]. Table I summarizes the publicly available sets of traffic matrices (and corresponding topologies) describing traffic demands between each node pair in the network. They cover time periods of up to 1 year, and having granularities of 5 min, 15 min, a day, or a month [8].

Power A survey of power consumption data available in literature and product data sheets can be found in [9]. It was extended toward a power model with reference power values [6] in the work led by Ward Van Heddeghem.

A selection of the above mentioned data is used in this work. Particularly, we show results for the Abilene and Germany17 networks in this work. We assume that power consumption of a single 40 Gbps line card is equal to 500 W. Details of all the investigated scenarios as well as values of Capital Expenditures (CapEx) costs, power consumption, and all the remaining parameters can be found in [1].

Testbed We use the IP-over-GbE testbed [10] located at the Institute of Communications and Information Technology (Istituto Superiore delle Comunicazioni e delle Tecnologie dell'Informazione ISCOM) of the Italian Ministry of Economic Development. The IP-over-GbE testbed was the only

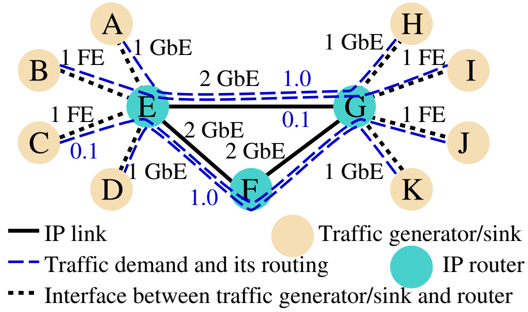


Fig. 3. Base logical topology (IP links realized with Gigabit Ethernet (GbE) and traffic generators/sinks attached with Fast Ethernet (FE)).

testbed available to us (Edion Tego and Francesco Matera from Fondazione Ugo Bordoni), however the same control and management mechanisms can be used for the IP-over-WDM and the IP-over-GbE networks. Optical GbE links are used instead of the WDM lightpaths for the sake of demonstration.

We configure the testbed in order to obtain a simple base logical topology (shown in Fig. 3 together with all traffic demands). The nodes A–D and H–K represent traffic generators and sinks attached to nodes E and G. The part representing a core network consists of the nodes E, F and G interconnected by three logical links, each formed by two GbE optical links.

The IP routing in the base network indicated in Fig. 3 has been chosen so that all the logical links carry traffic, and that the load exceeds the capacity of a single GbE optical link. It provides the opportunity to see what happens with the traffic on a logical link when the whole logical link or just one out of two parallel GbE links is switched off in a low-demand hour. Traffic details can be found in [1], [11]. Network control is centralized (Simple Network Management Protocol (SNMP)).

Power consumption of the IP routers with all interfaces shutdown equals 186.15 W and 112.5 W (for Juniper's M10 and M10i, respectively) according to our offline measurements. Power consumption of the GbE interfaces equals 11.07 W for the M10 router and 8.9 W for the M10i router.

III. Methodology

We present the steps that are performed in order to answer the three questions from Section I.

A. SBN design

Estimation of energy-savings that can be achieved with any EA-ARS requires a Static Base Network (SBN) as a starting point. The SBN determines devices (routers, line cards, number of fibers, OLAs, etc.) that are installed in the network and their initial configuration. In the extensive search (Section II-B) we found no complete set of input data (e.g., number of installed fibers on fiber links and their capacities missing). Therefore we design the SBN either solving the MILP formulation [1], [12] or with the Genetic Algorithm (GA) [13]. They both minimize CapEx (parametrized with the values from [5]) in their objective functions. We refer to the corresponding references for details of the SBN design.

B. Estimation of energy saving potential

Given the SBN, we propose three (classes of) approaches to save energy in low-demand hours.

Fixed Upper Fixed Lower (FUFL): Both the routing of IP traffic over the (upper) logical topology and the realization of lightpaths in the (lower) WDM layer are fixed over time. Demands are routed as in the SBN using the same lightpaths with the same percentual splitting as in the SBN. We allow to shift traffic between parallel lightpaths though. Line cards of empty lightpaths are switched off.

Dynamic Upper Fixed Lower (DUFL): The logical topology (including the realization of lightpaths) is fixed as in FUFL (Fixed Lower), but the routing of IP traffic can be changed (Dynamic Upper). In every demand scenario, we aim at routing the IP demands over the logical topology in such a way that as many lightpaths as possible are emptied in order to switch off the corresponding line cards.

Dynamic Upper Dynamic Lower (DUDL): Both the routing of the IP traffic in the logical layer and the realization of lightpaths in the physical layer can be changed over time (including adding lightpaths not existing in the SBN), with the restriction that the number of installed line cards at each IP router must not be exceeded. The number of used line cards is minimized by jointly optimizing the routing in the IP and WDM layers.

The terms Fixed Lower and Dynamic Lower apply to dynamics of the realization of the logical topology. Idle lightpaths are dynamically switched off in all the considered approaches. FUFL is a very simple and attractive approach for network operators [14]. It is fully distributed and involves neither changing of IP routing nor changing of the connectivity of the logical topology. DUFL and DUDL may have different realizations. We focus on the sohphisticated MILP formulations [1], [12].

C. A step toward reality - heuristic implementation

An EA-ARS needs to fulfill a set of challenges [1], [15] for computation of network configuration as well as for the timely triggering and network reconfiguration (Fig. 2). We propose an adaptive heuristic Energy Watermark Algorithm (EWA) for dynamic calculation of an energy-efficient network configuration [16]. EWA focuses on the IP layer.

EWA adapts the network to current traffic demands in order to save energy on one hand, and limit the load on logical links on the other hand. EWA uses a low and a high watermark (W_L and W_H) defined as thresholds on the utilization of the last lightpath on a logical link. Exceeding the W_H triggers attempts to establish additional lightpath(s) in order to avoid overload of the network. Exceeding the W_L triggers attempts to release lightpath(s) in order to switch off idle line cards and save energy. EWA makes sure that the maximum utilization of last lightpath on a logical link ψ is not exceeded when trying to release lightpaths.

Alg. 1 shows the main pseudocode of EWA. Details of its subroutines are presented in the appendix of [1]. The algorithm takes as input the network configuration in previous time

Algorithm 1 Pseudo-code of EWA.

Input: netConfig from period $t-1$, current traffic matrix $D(t)$, W, W_L, W_H, ψ

Output: Updated netConfig

1: ensureDemandsRoutability(netConfig, $D(t)$, W);

2: sortedLLsExceedingWMs = getSortedLLsExceedingWMs(netConfig, $D(t)$, W_L, W_H);

3: establishNecessaryLpaths(netConfig, $D(t)$, W, sortedLLsExceedingWMs, W_L, W_H);

4: releaseUnnecessaryLpaths(netConfig, $D(t)$, sortedLLsExceedingWMs, W_L, W_H, ψ);

period $t-1$ (network nodes V with installed line cards X_i^{LC}, established lightpaths forming logical links $y_l(t-1)$ and IP routing of traffic demands $f_{ij}^{ab}(t-1)$), traffic matrix $D(t)$ for the current time period t, capacity of a lightpath (WDM channel) W, W_L, W_H, and ψ. Updated network configuration is returned as output of the algorithm.

EWA first checks whether all the demands in the current network configuration are routable, and iteratively tries to establish additional lightpath(s) 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 flows through it. If this is not the case, attempts are made to establish lightpath(s) for the possibly biggest demand flowing through the overloaded logical link.

Once 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 per iteration is tried to be released making sure that ψ is not exceeded for Quality of Service (QoS) reasons. The order of first establishing lightpaths (line 2 of Alg. 1), and then attempting to release lighpaths (line 4 of Alg. 1) allows rerouting of traffic away from the lightpaths to be released (make-before-break mechanism).

D. Implementation on a testbed

We explain the methods used in each step needed for energy saving according to Fig. 2.

Traffic monitoring The most intuitive approach to traffic monitoring is to perform the monitoring constantly. This approach is impossible in the simulative works due to unavailability of input traffic data sets originating from measurements and covering traffic between all node pairs in the network over sufficiently long period of time with sufficient time granularity (IP packet arrival/departure level). An experimental activity overcomes this limitation. However, there is still some levels of freedom in setting the traffic monitoring in a digital system such as a telecommunication network (testbed), namely the time period T_M over which the constantly monitored

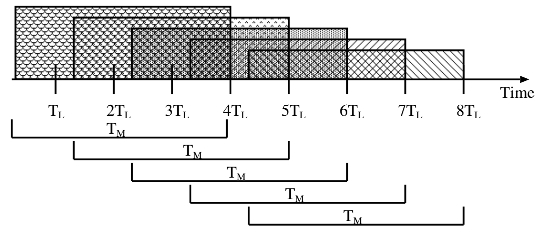


Fig. 4. Differentiation between T_M (time period over which the constantly monitored traffic is averaged) and T_L (the time period after which triggering events are validated).

traffic data is averaged and provided for evaluation triggering calculation of a new network configuration.

Validation of triggering events The second level of freedom determines the frequency at which the events triggering calculation of network configuration are validated. The related time period is denoted as T_L. Please note that T_L is different than T_M. The latter determines the history which is taken into account when validating triggering events, while the former determines the frequency at which the validation is performed (see Fig. 4). Calculation of new network topology is triggered by violation of load thresholds.

Calculation of network configuration We focus on the approaches FUFL and DUFL (Section III-B), but define thresholds (on utilization of logical links) triggering them. Namely, we define W_A and W_D for FUFL, and W_L and W_H for DUFL. The thresholds W_L and W_H have identical responsibilities as in EWA, i.e., their violation triggers attempts to release and establish lightpaths, respectively. W_A and W_D have similar responsibilities, i.e., activation and deactivation of lightpaths (no rerouting takes place in FUFL). The thresholds contribute to network stability by including a hysteresis cycle.

While FUFL implementation is straightforward, we assume the following implementation of DUFL here. The decision about an attempt to reroute traffic with the aim of deactivation or activation of a logical link is triggered by violation of the thresholds W_L and W_H, respectively. The traffic demands routed via E–F–G (Fig. 3) are attempted to be rerouted to link E–G if aggregated demand on the logical links E–F and F–G goes below W_L. An analogical rerouting attempt is performed when load of the logical link E–G goes below W_L. Idle logical links with optical interfaces are switched off. The original logical topology and routing (Fig. 3) is restored when W_H is violated on any logical link.

Network reconfiguration The last step concerns the application of the newly computed network configuration in network devices. To perform this step, the management system opens a telnet session on routers which need their configurations to be changed and applies the needed changes. Specifically, routing is changed and network interfaces are switched on/off according to the computed network configuration using commands specific for the Juniper routers. We ensure that rerouting is performed before a logical link is released when load decreases, and after a logical link is established when load increases.

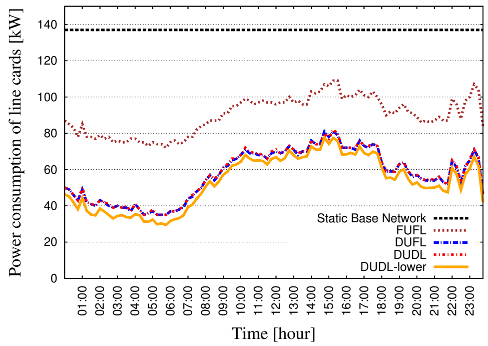


Fig. 5. Results for the Germany17 network with FUFL, DUFL, and DUDL (DFN traffic, 5 Tbps, every 15 minutes on 2005/02/15) [12].

IV. Results

We show selected results achieved with the approaches FUFL, DUFL, and DUDL, with the heuristic EWA, and with the testbed implementation. We use the following parameterization: $B = 80$ wavelengths per fiber, $W = 40\ Gbps$, $R = 80\ km$, CapEx values from [5], and power consumption values based on Cisco CRS-1 router (and line card) [9]. Detailed parameterization is shown in [1].

A. Power saving potential (FUFL, DUFL, DUDL)

A sophisticated MILP formulation [1], [12] is used to design the SBN. Fig. 5 shows power consumption of active line cards in the Germany17 network (loaded with DFN traffic [8] scaled to the maximum total demand of 5 Tbps, on 2005/02/15, time granularity of 15 minutes) when using no energy saving approach (SBN), and when using FUFL, DUFL, and DUDL. DUDL-lower denotes the lower bound for the DUDL-solution, where the exact optimum could not be found due to complexity of the optimization problem.

All the proposed approaches make use of traffic dynamics and follow the traffic day-night pattern. The power consumption of networks using DUFL and DUDL is nearly identical and much lower than when using FUFL. The flexibility of DUFL to reroute traffic saves a significant amount of power compared to FUFL. In contrast, reconfiguring the logical topology in the physical layer (DUDL) does not provide essential further benefits.

The simple approach FUFL allows to save substantial amount of power compared to SBN. The savings however depend on the ratio of the maximum total demand and the capacity of a single WDM channel W. If this ratio is low (traffic demands are low compared to lightpath capacity), there is little potential of savings with FUFL since a single lightpath might be sufficient to transport demands between pairs of nodes. Discussion of further results with varying load, network, time scale and demand pattern is shown in [1], [12].

B. EWA results

We compare the EWA performance with the Least Flow Algorithm (LFA) [17] and GA [13]. The GA is also used to design the SBN. Differently to most of other works, we distinguish a set of traffic matrices $D(t)$ corresponding to time periods $t \in T_{past}$ for the SBN design, and a set of traffic matrices $D(t)$ corresponding to time periods $t \in T_{fut}$ for evaluation of the energy savings when switching off idle devices in the SBN ($T_{past} \cup T_{fut} \in \emptyset$).

We present representative results from [1], [16] with $W_L = 0.1$, $W_H = 0.9$, and $\psi = W_H$ for EWA, $\delta = 1.0$ for LFA, $\alpha = 0.1$, $M = 500$, $S = 30$ and $\kappa = 20$ for GA. GA takes weighted (α) sum of power and reconfigured traffic as a fitness function. Other notation details can be found in [1], [16]. We focus on the SBN designed for traffic scaled to 300 Gbps (maximum total traffic per node in the Abilene network between 2005/07/01 and 2005/07/31). Results for Germany17 and Géant can be found in [1], [16].

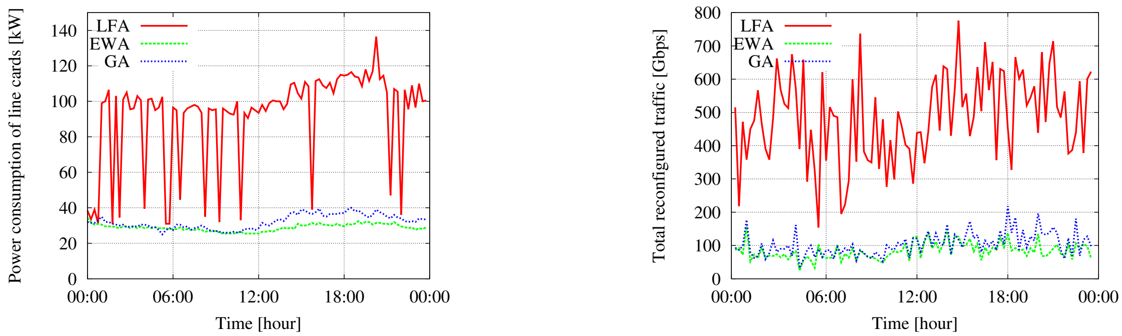
Fig. 6(a) shows power consumption of active line cards $P^{LC}(t)$ versus time. Similarly to the results from Fig. 5, $P^{LC}(t)$ follows a day-night trend of traffic when using EWA and GA. They both outperform LFA, which attempts to switch off whole logical links and not single lightpaths (hence the irregular spikes for LFA in Fig. 5). Variation of power over time is smoother with EWA than with GA due to the adaptive character of EWA. Similar results are observed for reconfiguration costs in terms of total reconfigured traffic (traffic that has to be rerouted due to network reconfiguration). EWA and GA outperform LFA achieving similar results. Despite its high worst-case complexity, the adaptive character of EWA leads to low computation times (median equal 0.01 s) compared to GA.

Further metrics (line card and total daily energy consumption, power of LCSs and FCSs, overload ratio, worst-case complexity, and yearly monetary costs) as well as impact of SBN, load variation and parametrization on the results are studied in [1], [16].

C. Testbed results

We parameterize the methods described in Section III-D in the following way: $W_D = 0.977$, $W_A = 0.985$ (FUFL), $W_L = 0.4885$, $W_H = 0.9925$ (DUFL), and $T_M = T_L = 10\ s$. The chosen values are determined by the generated traffic characteristic and for the sake of demonstration of the power saving approaches. Traffic variations close to the threshold values allow us to verify the methods without waiting long (corresponding to diurnal variation of traffic).

Fig. 7 reports the total power consumption and the power saving for the testbed running FUFL and DUFL on the logical topology. The total power consumption corresponds to power consumed by all active GbE interfaces together with the routers according to the data from Section II-B. Power consumption varies more frequently with DUFL than with FUFL, since our implementation of DUFL is more aggressive in turning off the network interfaces – it attempts to switch off the whole logical links. This in turn produces in general higher power saving compared to FUFL. The difference is minor due to the simple 3-node base logical topology and IP routing schemes that we use for this demonstration (see Fig. 3). No packets are lost.



(a) Power consumption

(b) Total reconfigured traffic

Fig. 6. Results for the Abilene network on 2004/08/27 (maximum total demand 300 Gbps per node) with EWA, LFA, and GA [16].

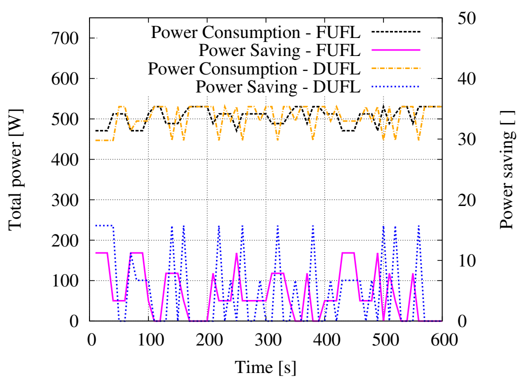


Fig. 7. Testbed results [11].

V. Conclusion & Future Work

Even the simple, fully-distributed approach FUFL provides potential of energy saving in IP-over-WDM networks switching idle line cards off during low-demand hours. Our results show that flexibility of IP routing contributes much more to the energy saving than flexibility of adaptation of logical topology (and its realization over the physical topology). The proposed adaptive heuristic EWA provides low power consumption of line cards in the network while limiting reconfigured traffic and computation time. The proposed energy saving concepts were successfully verified on an IP-over-GbE testbed.

There are several open issues regarding EWA and the collected realistic input data (traffic, topology and power values). First, protection needs to be taken into account when saving energy. Second, influence of physical constraints on energy saving approaches at the IP layer need to be studied. Eventually, we point out the need for new sets of traffic matrices originating from measurements due to changing traffic in the long-term. Particularly, variation of traffic load and its spatial distribution over time is currently under investigation.

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