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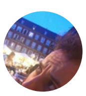
6 authors, including:

Antonio Cianfrani
Sapienza University of Rome

Jorge López Vizcaíno
ZTE Corporation



Marco Polverini
Sapienza University of Rome

Yabin Ye
Huawei Technologies

A Survey on Energy-Aware Design and Operation of Core Networks

Filip Idzikowski, Luca Chiaraviglio, Antonio Cianfrani, Jorge López Vizcaíno, Marco Polverini, Yabin Ye

***Abstract*—A detailed survey of approaches reducing energy consumption of core networks is presented in this work. We consider a multi-layer architecture, in which the optical layer can be realized either with a Wavelength Division Multiplexing (WDM) network or an Elastic Optical Network (EON). We focus on the design and operation stages, i.e., deciding which devices to install in the network during the former step, and choosing which devices to put into sleep mode during the latter one. A taxonomy for classifying the surveyed approaches is provided in order to compare the works covering energy efficiency in core networks (in terms of both optimal formulations and heuristic solutions). Moreover, our work provides a global view of the traffic assumptions, the topologies, and the power consumption models in the literature. The need of further investigations in this field clearly emerges. We envision future works targeting: (1) more effective standardization efforts to practically realize sleep modes, (2) the evaluation of the impact of sleep mode on the device lifetime, (3) the extensive adoption of new paradigms like Software Defined Networking (SDN) and EON, and (4) a radical improvement in the testbed implementations.**

***Index Terms*—survey, optical communications, green networking, energy efficiency, power consumption, routing, sleep mode, traffic, topologies, network scenarios**

I. INTRODUCTION

Reducing energy consumption of the processes introduced by the mankind has become a mandatory goal in recent years. This issue has several root causes, varying from the reduction of emissions of green-house gases, through the monetary saving in the electricity bills, up to the exploitation of renewable power sources.

Among the energy-consuming sectors, the Information and Communication Technology (ICT) sector is rapidly becoming a big player. Recent studies have shown that the ICT impact on global power consumption is non-negligible, ranging from 2% to 10% [1]. This is due to the proliferation of electronic devices and the power-expensive manufacturing processes required to produce such devices. Moreover, a 3-fold increase in global ICT-related electricity consumption is projected by 2030 compared to 2013 [2].

The three main areas in the ICT sector are: telecommunication networks, data-centers, and mobile terminals. According to [1], telecommunication networks consume ca. 37% of the ICT power consumption and some astonishing data enforces this estimation. According to [3], Telecom Italia is the second largest consumer of electricity in Italy after the National Railway system, consuming more than 2 TWh per year. Similar and even more pessimistic considerations also hold for other developed countries (see for example [4] for the case of Japan).

F. Idzikowski is with Poznan University of Technology, Faculty of Electronics and Telecommunications, Poznań, Poland (e-mail: filip.idzikowski@put.poznan.pl).

L. Chiaraviglio, A. Cianfrani, and M. Polverini are with the DIET Department, Sapienza University of Rome, Rome, Italy (e-mail: {firstname.lastname}@uniroma1.it).

J. López Vizcaíno and Y. Ye are with HUAWEI Technologies Duesseldorf GmbH, Munich, Germany (e-mail: {jorge.vizcaino |yabin.ye}@huawei.com).

Traditionally, telecommunication networks have been designed to maximize the available bandwidth and its exploitation [5]. This policy tends to minimize the replacement costs that occur when technologies are updated to meet an increase either in the number of users or in the exchanged traffic. However, users access the network at different times of the day and the applications used are different in terms of exchanged traffic. Networks are dimensioned for the highest traffic demands, so that the quantity of data flowing in the network is normally well below the maximum achievable data rates [6].

Power consumption of network devices normally depends on the installed capacity of the underlying technology [7]. In fact, network devices are designed to maximize performance metrics, like the device capacity. As a result, a network device consumes an amount of power independent from the current quantity of data that the device is processing.

The main idea of Energy-Aware (EA) network design and operation is to reduce the gap between the utilization of the network and the offered capacity. Starting from the pioneering work of Gupta et al. [8] different solutions are being studied to reduce the energy waste, or, equivalently, to make the network consumption proportional to the traffic load [9, 10]. The proposed approaches can be divided into two main categories: (1) energy-proportional approaches that address individual devices and try to achieve energy proportionality by adapting the speed (and capacity) of the devices to the actual load, and (2) sleep mode approaches that affect the network as a whole and approximate load proportionality by carefully distributing the traffic in the network so that some devices are fully utilized and other devices become idle and are put into sleep mode. In particular, sleep modes are motivated by the fact that energy consumption of current devices is practically independent from the load [7, 11]. Therefore, switching off the devices can save a consistent amount of energy. However, sleep modes introduce an additional level of complexity to the network. In fact, coordination among devices is required. In particular, traffic has to be re-routed from the devices that are going to be powered off to other devices that remain on. Choosing which devices to power off is an open problem. Then, the network has to implement mechanisms to react to traffic increases, i.e., by choosing which devices have to be powered on. Finally, the network has to implement mechanisms to guarantee Quality of Service (QoS) for users when energy-saving approaches are implemented.

A. Scope of this work

We investigate the problem of designing and operating EA core networks adopting sleep modes, by providing a deep understanding of the network models, formulations, algorithms, network scenarios, and QoS metrics. We consider works covering either the Internet Protocol (IP) layer, or the optical layer, or both of them. Our goal is to provide a comprehensive survey of the solutions proposed so far, and to provide several guidelines for future relevant investigations in this field.

In the past, different surveys [9, 12–15] have been published on the topic of energy-efficient core networks. However, their scope is in general wider (and thus less detailed) than this work. They cover different aspects, including wireless and wired networks, the design of EA devices, the adoption of speed scaling techniques, computing resources, etc., while here we mainly focus on the adoption of sleep mode techniques to achieve energy saving in core networks. Moreover, our work covers a higher number of Energy-Aware Network Design (EA-ND) and Energy-Aware Network Operation (EA-NO) approaches proposed in the literature. In particular, we have reviewed, classified, and extracted relevant information from more than 300 papers, making a single work which covers all the aspects relevant to EA core networks exploiting sleep modes. We have also considered the field of EA EONs, SDN and impact of energy saving on device lifetime. These fields are not covered by previous works apart from EON briefly tackled in [14]. Finally, none of the previous surveys looked at network scenarios, which are critical to evaluate energy savings achieved with EA-ND and EA-NO.

Additionally, the survey article [16] mainly focuses on a methodology to compare the power saving obtained by the different approaches. Our work is complementary to [16], since: (1) we are more focused on investigating the formulation and algorithmic aspects of the different approaches, (2) we consider different features to classify the approaches apart from power consumption.

Table I compares this paper with the other related survey papers focusing on the novel aspects of this work. The aspects covered by other survey papers, which are out of scope of this work, are not listed in Table I.

In order to make our survey focused and comprehensive, we explicitly leave out the articles focusing on node architectures (e.g., [17]), investigating energy savings in data centers (e.g., [18]), clouds (e.g., [19]), and considering caching (e.g., [20]), multicasting (e.g., [21]) as well as controlling traffic outside of the core network (e.g., [22, 23]).

B. Outline

Fig. 1 reports the outline of this work. The assumed network model is detailed in Section II, considering first the IP-over-WDM scenario, and then focusing on the EON one. Section III is devoted to the EA-ND problem. In particular, a taxonomy of the main features considered in this part is reported in Section III-A. Then, the different network layers are considered. More in depth, we start from the optical layer in Section III-B, then we consider the IP layer in Section III-C, and finally we consider jointly the optical and the IP layers. For each layer, we report the formulation of the problem, and the algorithms comparison in the light of the main features that we have selected. Section IV is devoted to EA-NO, following the same structure as in Section III. Then, Section V reports the network scenarios covered by the literature, differentiating between: (1) traffic data (Section V-A), (2) network topologies (Section V-B), and (3) power models (Section V-C). Moreover, Section VI reports a discussion of the main issues that emerge from the different approaches, with emphasis on: (1) the main parameters enabling sleep mode approaches (Section VI-A), (2) the QoS metrics (Section VI-B), and (3) future trends (Section VI-C). Finally, Section VII concludes our work. All acronyms used in this work are explained in the appendix.

II. Network Model

We first detail the model for the IP-over-WDM network in Section II-A. We then detail the modification of the model for

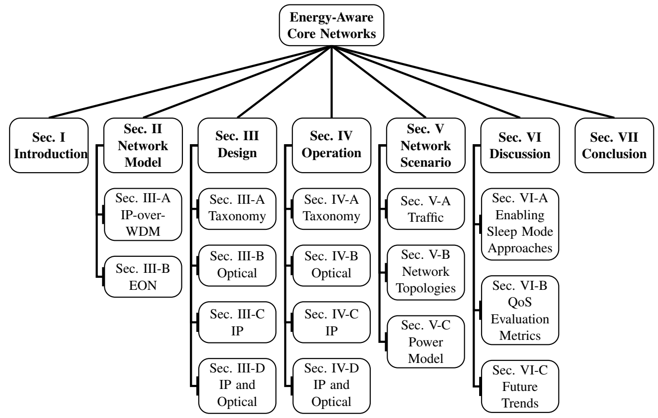


Fig. 1. Outline of the paper.

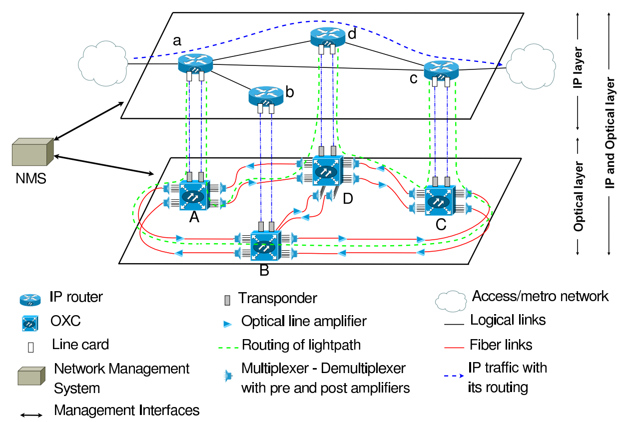


Fig. 2. Network model for the IP over optical scenario.

the EON scenario in Section II-B. Explanation of the models is supported by Fig. 2.

A. IP-over-WDM

We consider a core network composed of two layers, namely the IP layer and the WDM layer. The IP layer represents the Logical Topology (LT) and is composed of routers and logical links[1]. One of its main goals is to aggregate data traffic coming from access and metro networks. An example of traffic demand exchanged between access networks is depicted in Fig. 2 as a blue dashed line. The IP layer is also responsible for routing traffic demands over the LT. The same traffic demand can be routed along one path or split over multiple paths, i.e., considering Single-Path Routing (SPR) or Multi-Path Routing (MPR). Nodes in the LT may be logically connected to many other nodes which improves the reliability in case of a link failure. For instance, looking at Fig. 2, if the logical link connecting node a to node c fails, node a is still able to reach node c via node d. On the contrary, if the logical link between nodes a and b fails, then node b is disconnected from the network.

Each router in the IP layer is connected to an Optical Cross-Connect (OXC) in the optical layer by means of colored Line Cards (LCs) or gray LCs and TranSPonders (TSPs). LCs and TSPs are in charge of Optical-Electrical-Optical (OEO) conversion and signal regeneration (REGenerators (REGs) are realized as back-to-back LCs/TSPs). OXCs in the optical layer are interconnected by

[1]The terms “logical” and “virtual” are used interchangeably in the literature. We prefer the term “logical”.

TABLE I
NOVEL ASPECTS OF THIS WORK WITH RESPECT TO THE RELATED SURVEY PAPERS.

Survey paper	Scope	Focus of This Work in the context of Backbone Networks: Network Design	Network Operation	Network Scenario	Research directions: EON	SDN	Lifetime
Zhang, 2011 [12]	core, metro, and access networks, data centers, and applications (proxying, green TCP/IP protocol design, grid computing)	✓	✓(selectively turning off network elements, energy-efficient IP packet forwarding, green routing)	–	–	–	–
Bolla, 2011 [13]	wired access networks, wireless/cellular networks, routers and switches, network and topology control, green Ethernet, end-users and applications	– (only re-engineering of network devices, i.e., silicon, complexity)	✓(dynamic adaptation (power scaling and idle logic), sleeping/standby (proxying))	–	–	–	–
Bianzino, 2012 [9]	wired (focus), wireless communications, computer and data center architectures	–	✓(ALR (sleep mode, rate switch), interface proxying (LC and external proxying), energy-aware infrastructure (applications and routing), energy-aware software (user-level and kernel-level applications))	– (power measurements surveyed)	–	–	–
Orgerie, 2014 [15]	computing resources, wired networking resources	– (only hardware, Clean-Slate approaches)	✓(shutdown (on/off and sleeping methods, proxying), rate adaptation, network-wide management (coordination))	– (measuring and modeling of energy consumption surveyed)	–	–	–
Dharmaweera, 2015 [14]	backbone networks	– (only node redesign and physical topology redesign)	✓(Traffic Engineering (wavelength, waveband, multicast grooming), Power Aware Networking (design, routing, switch-off/sleep mode), Load-adaptive operation (SLR/MLR, ALR))	– (adapting of approaches in real networks and power consumption values surveyed)	✓	–	–
Van Heddeghem, 2015 [16]	IP-over-WDM backbone networks	✓(analytical model, quantitative survey)	✓(analytical model, quantitative survey)	– (power rating values for the analytical model)	–	–	–
This work	backbone networks	✓(detailed survey)	✓(detailed survey)	✓(traffic, network topologies, and used power values surveyed)	✓	✓	✓

means of physical links composed of one or more fibers. A pair of MUltipleXers (MUXs)/DEMUltipleXers (DEMUXs) is used on each fiber to multiplex/demultiplex wavelengths spaced according to the fixed International Telecommunication Union – Telecommunication standardization sector (ITU-T) grid. In addition, for long distance transmission, Optical Line Amplifiers (OLAs) are used to amplify the optical signal in each fiber.

A logical link in the IP layer is represented by a lightpath (or bundle of lightpaths with the same source node and target node) in the optical layer. In case wavelength conversion is needed, we assume that it can be performed by WaveLength ConverTers (WLCTs) installed inside the optical nodes. As an example, three lightpaths are shown in Fig. 2. One lightpath represents the logical link between routers a and c, one realizes the logical link between nodes d and c, and the third one represents the logical link between nodes a and d.

To give an idea of how an IP-over-WDM network works, let us explain the routing of the traffic demand depicted in Fig. 2. In the IP layer the traffic demand follows the path $a-d-c$, by traversing the logical links ad and dc. These two logical links are realized by means of two lightpaths in the WDM layer, represented in Fig. 2 by green dashed lines. More precisely, at router a, each packet is converted to an optical signal by means of LC/TSP, and sent via OXC A to the physical (fiber) link toward OXC D. The optical signal is modulated on the proper wavelength, multiplexed together with other wavelengths by the MUX, and amplified by an OLA. A DEMUX placed at OXC D is in charge of demultiplexing the optical signal from the proper wavelength. Then, the optical signal is converted to an electrical signal, and sent back to the IP layer by means of TSP/LC. Here router d sends the packet toward the router c by means of the logical link dc (and analogically OXCs D and C). Finally, the router c forwards the packet to the destination network. It must be noted that the traffic demand depicted in Fig. 2 could potentially take the direct logical link from router a to router c, or be split over the two paths $a-c$ and $a-d-c$. Similarly, each lightpath needs to be routed in the optical layer (see particularly the lightpath connecting routers a and c routed via OXC B) and assigned a wavelength. This problem is called Routing and Wavelength Assignment (RWA).

Eventually, Network Management System (NMS) is necessary to dynamically reconfigure the network. NMS is obviously needed also for network maintenance.

B. Elastic Optical Network

Flexible grid network or EON has been recently proposed as a potential technology candidate to overcome the tremendous traffic growth at the optical layer [24]. EON offers a more efficient utilization of the spectral resources thanks to the flexible spectrum allocation (finer spectrum granularity than the ITU-T grid of WDM networks) and the rate adaptation. Two novel network elements are required for the operation of EON: (1) Bandwidth Variable TranSPonder (BV-TSP) which allows for changing the transmission bandwidth and/or the modulation format, and (2) Bandwidth Variable OXC (BV-OXC) which is able to switch different-bandwidth optical signals. RWA algorithms used for planning of WDM networks are no longer valid when moving to EON due to the contiguous allocation constraint (subcarriers of a channel must be assigned in a contiguous manner) and the presence of different modulation formats. In this context Routing and Spectrum Allocation (RSA) and Routing, Modulation Level and Spectrum Allocation (RMLSA) are needed.

III. Energy-Aware Network Design

Taxonomy used for the EA-ND approaches is presented first. Then, we classify the EA-ND approaches according to the layer(s) of the devices targeted to save energy by the algorithms. The methods targeting separately the optical and IP layers are described first. The methods targeting jointly the IP and optical layers are described next.

We consider the devices targeted during the execution of the algorithm as the main criterion to classify the approaches to the corresponding layer(s). However, an EA-ND approach may compute power consumption of devices belonging to different layers in the results evaluation, while the algorithm only targets reduction of power consumption of one layer only. Additionally, routing constraints may span across different layers, while the targeted devices belong to one layer only. In our work, such specific cases do not influence the classification of an approach to the corresponding layer.

To improve the readability of this paper, we proceed in the following way. For each layer, we first provide a scheme of the problem formulation, and then we provide a comparison of the surveyed approaches together with a table summarizing their main features. We use the following notation in the table in order to keep them compact: n/a – not applicable, n/c – not considered, n/r – not reported, ppr – postprocessing. Similar approaches are reported together in the table. E.g., the heuristics Least-Cost Path (LCP), Most-Used Path (MUP), and Ordered-Lightpath Most-Used Path (OLMUP) proposed in [25] are reported together, because the difference between them is only the assignment of link weights and order of serving lightpath requests. Similarly, Mixed-Integer Linear Programming (MILP) formulation and corresponding heuristics are jointly reported in case they belong to the same work. In some cases, we keep together similar approaches for the WDM networks and EONs.

A. Taxonomy

The main aim of the network design process is to choose devices **to be installed** in the network. The devices include OXCs, OLAs, WDM terminals, REGs and TSPs in the optical layer, and routers (including different chassis/shelves/racks) and LCs in the IP layer. Different terminologies or levels of details of network modeling are used in the surveyed work. Short Reach (SR) interfaces, router interfaces, Network Interface Cards (NICs), capacity modules, line modules, Transmitters (TXs), Receivers (RXs), transceivers correspond to LCs and TSPs. Switching matrices, switching fabrics and 3-dimension Micro Electro-Mechanical Systems (MEMSs), Arrayed Waveguide Grating (AWG) filters correspond to OXCs. In some cases fixed power consumption and variable power consumption (depending on load) are distinguished. The variable power consumption corresponds to processes such as OEO conversion (at LCs and TSPs), electrical switching, IP processing (at routers), as well as optical switching (at OXCs). Furthermore, the greenfield EA-ND approaches determine **installation of fibers**, while the non-greenfield EA-ND approaches assume that fibers are pre-installed in the network (which does not exclude installation of additional fibers).

We distinguish methods of **IP traffic routing** over the LT (either SPR with a potential constraint on Shortest Path Routing (ShPR) or MPR) and **routing of lightpaths** over the physical topology (again either SPR with a potential constraint on ShPR or MPR). Next, we consider the approach to the wavelength continuity problem, which includes potential usage of **wavelength conversion** and **Wavelength Assignment (WA)**. In general, both of these aspects are complementary and can potentially be done in a postprocessing step in order to decrease the complexity of the network design problem.

Furthermore, we look for constraints ensuring **QoS**, which in the network design mainly correspond to the constraint on the maximum level of utilization of network resources (overprovisioning). The overprovisioning can be performed already at the stage of the estimation of the peak traffic that the designed network will handle. Next, we look at the indication of **computation time** or complexity of the given approach. Fast computation is not critical for the network design methods in contrast to the EA-NO. The provided information is purely indicative since it depends on network size, amount of devices that can potentially be installed in the network, implementation, and computation platform. Computation time of MILP problems is labeled as “hours” regardless whether it is reported in the corresponding paper or not. In particular, it is possible to stop the MILP solver after a given amount of time, however no limitation of optimization gap can be guaranteed then. Consideration of **protection** is the final aspect of the survey.

Some of the above mentioned criteria can be neglected when looking at single layers. **Optical layer:** The criteria purely related to the IP layer do not apply. They include IP routing of traffic demands over the LT. However, since the routing of lightpaths over the physical topology is considered, and all parallel lightpaths with the same source and target nodes constitute a logical (IP) link, the design of LT is covered indirectly by these network design approaches.

IP layer: The criteria purely related to the optical layer are usually not considered. They include installation of fibers, routing of lightpaths in the optical layer as well as wavelength conversion and assignment.

B. Optical layer

Section III-B1 details the problem formulation, while Section III-B2 presents the comparison of the surveyed approaches.

1) Formulation: The problem of EA design of optical networks can be formulated with an optimization model[2], which is reported in Fig. 3. In particular, the objective function targets the reduction of power of different optical devices, considering: OXCs, TSPs[3], OLAs, TXs, and RXs. Power incurred by the optical switching may also be considered. Moreover, more generic cost functions (considering power consumption of nodes, servers or links) may

[2]Simple constraints (such as non-negative number of fibers installed on a physical link or the constraint that a link can be powered off only in case its load is equal to 0) are not shown in all formulations presented in this work in order to limit their size.

[3]We assume that OEO conversion is performed inside TSPs.

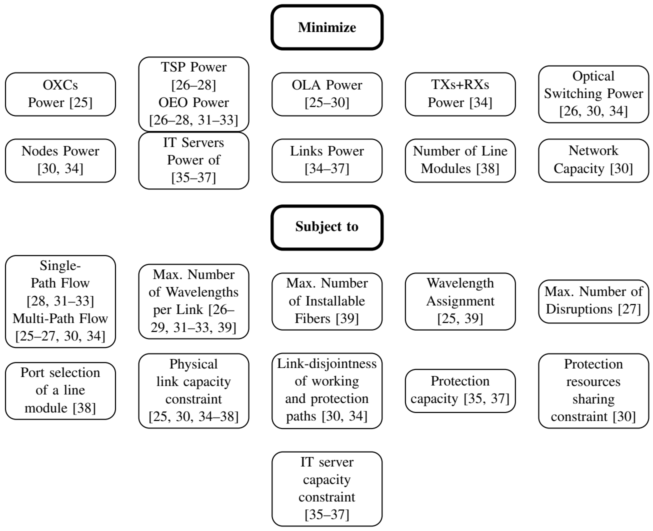


Fig. 3. MILP formulation for the Energy-Aware Network Design (EA-ND) – optical layer.

be taken into account. Additionally, the number of line modules may be integrated in the objective function. Finally, minimization of the total installed network capacity may be considered, since normally network devices consuming the highest amount of power are also the ones with the highest capacity. A weighted function of capacity and energy is considered in [30].

Focusing then on the constraints, traffic (lightpath requests) has to be routed in the network, considering either a single-path or a multi-path flow constraint. Moreover, the number of wavelengths is bounded for each link to a maximum value. Eventually, also the WA and the maximum number of installable fibers may be taken into account. Additionally, if the network is upgraded, i.e., some devices have already been installed while other devices need to be installed, a constraint limiting the maximum number of disruptions is introduced. A disruption is defined as lightpath termination being a consequence of traffic increase which imposes creation of a new lightpath during the network upgrade, or being a consequence of additional impairments (e.g., crosstalks, cross phase modulation, etc.) caused by new lightpaths. Other constraints include port selection of a line module and, more frequently, the maximum physical link capacity.

Moreover, protection constraints may be considered. In particular, the working and protected paths for each source node and each target node may be required to be disjoint. Additionally, part of the link capacity must be reserved to carry the protected traffic. Finally, a constraint limiting the amount of shared resources may be inserted.

In case the design phase takes into account the Information Technology (IT) servers infrastructure, a constraint limiting the maximum capacity of the installed IT infrastructure (and in particular of the servers) may be included.

2) Comparison of Approaches: Table II reports the main features of the approaches. We have differentiated among the following categories: (1) OXCs and other devices, and (2) other devices.

OXCs and Other Devices: This category covers OXCs together with TSPs, OLAs, MUXs, DEMUXs, and WLCTs. WDM is more frequently assumed than EON at the optical layer in this category. The installation of fibers is not considered in most of the works (except for Power-Aware Reliable Design (PARD) [40]), i.e., either the physical connectivity is assumed to be known (and the design phase takes care of choosing which devices to install taking into account the physical connectivity as a constraint) or full connectivity with infinite capacity of fiber links is assumed.

Focusing then on routing, it is considered only in the optical layer. Several works assume SPR, mostly with ShPR and power consumption of network elements used as link weights. Interestingly, only MILP based approaches consider MPR at the optical layer. This is due to the fact that MPR routing is simpler to manage for a MILP solver than SPR.

The wavelength conversion is either not considered or not reported or allowed, suggesting that this aspect is less critical for the design phase. On the contrary, the WA problem is normally solved for most of the works, with the First Fit (FF) heuristic being the most popular WA approach (and the easiest one to implement). Regarding the QoS constraint, it is not considered in most of the works. This is due to the fact that the optical design phase is devoted to the selection of the set of devices to install in the network to meet the forecasted traffic demands.

Focusing on computation time, the MILP solutions are obtained even after some hours. This is a reasonable amount of time, since the design phase is normally decoupled from operation of the network. The heuristic approaches require several minutes to complete the network design.

Finally, protection is considered in about half of the works. This result indicates that protection is particularly important when targeting OXCs for energy saving. An OXC represents a physical node in the network. It is usually traversed by multiple lightpaths. Its failure is critical for network operation. For the works considering protection, it is also interesting to note that there is no preferred method to ensure this constraint, i.e., different schemes are used (e.g., Shared Path Protection (SPP), Dedicated Path Protection (DPP), etc.).

Other Devices: This category covers TSPs, OLAs, and WLCTs. The surveyed approaches consider EONs only to a limited extent. However, since this paradigm will likely be adopted in future networks, we believe that a deeper investigation of green EONs is of mandatory importance. IP routing is not applicable in this category, and SPR with ShPR constraint (mainly based on geographical distance) is mostly used for the routing of lightpaths over the physical topology. Three approaches consider fiber installation. Wavelength conversion and wavelength assignment are tackled in a similar way as in the previous category. Regarding the QoS constraint, it is not considered in most of the works, but we point out minimization of consumed wavelengths as a secondary MILP objective [29], restriction on a maximum number of hops [29] and blocking probability [31–33] as potential ways to address the QoS requirements. Computation time (ranging from seconds to hours) is not critical for the network design approaches. Finally, in this case the protection is not as relevant as in the previous category. This is due to the fact that switching off a device from this category is less critical in terms of network reliability with respect to the removal of an OXC.

Overall, the surveyed EA-ND approaches targeting devices in the optical layer cover together all the evaluation criteria shown in Table II. We stress that each single approach proposed in the future should consider all the evaluation criteria, and particularly protection and installation of fibers (or a constraint on the capacity of the installed fibers).

TABLE II: Energy-Aware Network Design (EA-ND) approaches targeting power saving in optical layer.

Method's Name, First author(s), Year of the first publication	Optical layer	Devices to install	Installation of fibers	Routing IP	Routing Optical	Wavelength conversion	Wavelength Assign.	QoS constraint	Computa-tion time	Protection considered
OXCs and Other Devices targeted for power saving										
MILP [35–37], Tzanakaki 2011	WDM	IT servers, OXCs, TSPs, OLAs	no	n/a	MPR	n/r	n/r	n/c	hours	1:1
EASPP [41], Jalalinia 2012	WDM	electronic processing, OLAs	no	n/a	SPR, ShPR with power consump-tion and capacity usage	no	FF	n/c	n/r	SPP
PARD [40], Kantarci & Mouftah 2010	WDM	OXCs, TSPs OLAs, MUXs, DEMUXs	yes	n/a	SPR	n/c	n/c	n/c	n/r	SPP
Power-Aware Provisioning with Auxiliary Graph [42, 43], Xia 2010	WDM	OXCs, TSPs, OLAs	no	n/a	SPR, ShPR over auxiliary graph	Allowed at OEO	n/c	n/c[4]	n/r	no
ILP [34], Muhammad 2010	WDM	OXCs, TSPs, OLAs	no	n/a	MPR	full	n/c	n/c	hours	1:1 dedicated
ILP [30], Çavdar 2010	WDM	OXCs, TSPs, OLAs, WLCTs	no	n/a	MPR	full	n/c	n/c	hours	shared
Reach-adapting RWA, RMLSA [44, 45], Palkopoulou & Angelou 2012	WDM, EON	OXCs, TSPs, OLAs	no	n/a	SPR, ShPR with geographical distance	no	FF	n/c	n/r	no
GGA (ILP and heuristics) [46], Wu 2014	EON	OXCs, TSPs, OLAs	no	n/a	SPR, ShPR with geographical distance	at 3R REGs	FF	n/c	n/r	no
EE Amplifier placement optimiza-tion [47–49], López Vizcaíno 2014	WDM	OXCs, TSPs, OLAs	no	n/a	SPR, ShPR with EEPG	no	FF	blocking	mins.	none in [48], DPP 1+1 in [47, 49]
EA-RWA, EA-RMLSA [50–52], López Vizcaíno 2011	WDM, EON	OXCs, TSPs	no	n/a	SPR, ShPR with power consump-tion values	allowed at OEO	FF	n/c	mins	no
Survivable EA-RWA, EA-RMLSA [53–55], López Vizcaíno 2012	WDM, EON	OXCs, TSPs	no	n/a	SPR, ShPR with power consump-tion values	no	FF	n/c	mins.	SPP, DPP 1+1, DPP 1:1
Diff QoP EA-RWA, EA-RMLSA [56–58], López Vizcaíno 2013	WDM, EON	OXCs, TSPs	no	n/a	SPR, ShPR with power consump-tion values	no	FF	n/c	mins.	SPP, DPP 1+1, DPP 1:1
EA-RWA, EA-RMLSA (with em-bodied energy) [59, 60], Mata 2013	WDM, EON	OXCs, TSPs	no	n/a	SPR, ShPR with over-all energy consump-tion (em-bodied + operational)	no	FF	n/c	mins.	no
LCP, MUP, OLMUP [25], Wu 2009	WDM	OXCs, OLAs	no	n/a	SPR	no	FF	n/c	n/r	no
SM based MG-OTN design and planning [61–64], Naas 2011	WDM	OXCs, OLAs	no	n/a	SPR	at OEO	consid.	n/c	n/r	no

Continued on next page

[4]Blocking probability analyzed in [42, 43].

TABLE II Energy-Aware Network Design (EA-ND) approaches targeting power saving in optical layer – continued from previous page.

Method's Name, First author(s), Year of the first publication	**Optical layer**	**Devices to install**	**Installation of fibers**	**Routing IP**	**Routing Optical**	**Wavelength conversion**	**Wavelength Assign.**	**QoS constraint**	**Computation time**	**Protection considered**
Other Devices targeted for power saving										
MILP [27], Nag 2012	WDM	TSPs, OLAs	yes	n/a	SPR	n/c	n/r	n/c	hours	no
MILP [26], Nag 2013	WDM, EON	TSPs, OLAs, WLCTs	yes	n/a	MPR	at OEO	consid.	n/c	hours	no
EE-FON [28], Khodakamari 2014	EON	TSPs, OLAs , WLCTs	no	n/a	SPR, ShPR with geographical distance	Allowed at 3R REGs	FF	n/c	seconds	no
ILP [38], Morais 2013	WDM	TSPs	yes	n/a	SPR, ShPR	n/c	n/c	n/c	hours	no
Split-step method and OPNET SP Guru Transport planner (black-box) [65, 66], Silvestri 2009	WDM	OLAs	n/r	n/a	n/r	n/r	OPNET	n/c	n/r	1+1 DiPP
MILP, MFA [29], Shen 2011	WDM	OLAs	n/r	n/a	n/r for MILP, SPR, ShPR with link weight (number of OLAs or cost ε) for MFA	no	n/r	min. of tot. consumed wavelengths (secondary MILP objective); max. hops	n/r	n/r
Energy-efficient resilience with MRP, ILP and heuristics [31–33], Chen 2012	EON	OLAs	no	n/a	SPR, ShPR with geographical distance	Allowed at 3R REGs	FF	blocking probability (dynamic scenario)	n/r	P-cycles and SPP

C. IP layer

Section III-C1 details the problem formulation, while Section III-C2 presents the comparison of the surveyed approaches.

1) Formulation: We consider the formulation of the problem of reducing power consumption in the design of the IP layer (Fig. 4). Focusing on the objective function, power consumption of routers (including or not the amount of power due to traffic processing), LCs or IP links are normally taken into account. The number of installed LCs can be also used as objective function. Another objective is the minimization of the sum of the weights of the installed links (which is particularly effective in saving energy when the weight is proportional to the link power consumption). Moreover, a second term that can be added is the minimization of the network diameter, i.e., the longest of all shortest paths between any node pair in the network [67]. Clearly, this term is in contrast to a pure energy-minimization problem, and therefore a weight parameter should be introduced. Another possible objective is the minimization of non-renewable energy consumption, assuming a scenario in which some of the devices can be powered by renewable sources and the others by non-renewable ones. Finally, a trade-off between power and performance can be alternatively used as an objective function.

Focusing then on the constraints, the traffic has to traverse the network either through SPR or MPR. Moreover, the node and the link utilization should not exceed their capacity. Additionally, the number of disjoint paths should be limited, in order to avoid the case in which a single traffic demand is split across different paths which may lead to packet reordering and therefore QoS degradation. Moreover, the maximum allowable network diameter can be introduced.

When designing the network at the IP layer, it is also critical to reserve network resources for protection purposes. In this scenario, a constraint guaranteeing a backup path which is disjoint in terms of nodes traversed from the primary one may be introduced.

2) Comparison of Approaches: Table III reports the main characteristics of the approaches. In particular, we have differentiated among the following categories: (1) Routers and other devices, (2) LCs and other devices, and (3) other devices.

Routers and Other Devices: This category covers routers together with LCs. The underlying optical layer is not considered in the surveyed works. Even in this case (i.e., when optical devices are not targeted for power saving), future works should consider the optical layer and its constraints. Exploitation of the optical bypass is a crucial key in the reduction of the electronic processing contributing to energy consumption. The installation of fibers is clearly not considered.

The routing at the IP layer is performed as MPR. This choice may be motivated by the fact that both of the proposed approaches are MILP formulations, and the formulation of the optimization problem considering an MPR routing is simpler to solve for a MILP solver than a SPR one (all the routing variables are real numbers instead of integer ones).

Obviously, the routing at the optical layer, the wavelength conversion and the wavelength assignment are not considered, since none of the proposed works tackles the optical layer.

Similar to the EA-ND targeting devices in the optical layer (Section III-B2), QoS constraints are not mandatory. Moreover, a solution may require even some hours of computation, as this constraint is not strict during the network design phase. Finally, we can see that protection is not considered. Further work is required in this area, since no protection of router failures may lead to serious interruptions of network operation (particularly when some operational routers are in sleep mode).

LCs and Other Devices: This category covers LCs together with TSPs. Differently from the case in which the devices to install are routers, WDM is always assumed for the optical layer. Nevertheless, wavelength conversion, wavelength assignment, and optical routing are not considered (except for the MILP formulation described in [68]). At the IP layer the routing can be either SPR or MPR. When the SPR is assumed, a ShPR policy is usually applied. Existence of non-sleep enabled LCs in the MILP formulation [68] is the only attempt to comply with QoS constraint. Finally, even though the protection against failures is less critical in this case than in the case in which routers are the devices to install, this aspect is addressed in the MILP formulation [68].

Other Devices: This category covers transmitters, receivers, and IP links. The optical layer is specified only in [69, 70] (MILP formulation, Less Energy Incremental (LE-I), and Genetic Algorithm (GA)), while the installation of fibers is considered in none of the works. In the IP layer the routing can be either SPR or MPR, depending on the considered approach. Routing at the optical layer, as well as wavelength conversion and wavelength assignment are never taken into account.

The constraint on QoS is not taken into account by any approach, however number of hops is analyzed in [70] as an evaluation metric. The computation time is either not reported or in the order of hours. Finally, protection is considered only in the ADDing edges algorithm (ADD) and DELeting Edges algorithm (DEL) [67].

D. IP and optical layers

Section III-D1 details the problem formulation, while Section III-D2 presents the comparison of the surveyed approaches.

1) Formulation: Fig. 5 reports the problem formulation for the EA design of IP and optical layers. Focusing on the IP layer, power consumption of IP routers and LCs is considered (sometimes with a more general model for electronic traffic processing). Focusing then on the optical layer, power consumption of OXCs (sometimes with a more general model for optical switching), TSPs, OLAs is generally taken into account. Additionally, power consumption of specific optical devices, such as WDM terminals, REGs, MUXs and DEMUXs may be also considered in the objective function. Moreover, the reduction of the total amount of flow may be taken into account as an additional term in the objective function (introduced with a weight parameter), in order to avoid the traffic concentration on few devices, which may negatively impact the protection of the traffic demands in case of failures. Furthermore, the number of installed ports may be considered. Finally, the minimization of the network embodied energy, (i.e., the energy used for manufacturing and maintaining the installed devices) and the amount of non-renewable energy consumption (assuming that part of the energy can be derived from renewable sources) may also be part of the objective function.

Looking then at the constraints, traffic has to be routed in the IP and optical layers, considering either single-path flow or multi-path flow constraints. Capacity constraints should be introduced at both layers, i.e., considering the logical link capacity and the physical link capacity (i.e., the capacity of the whole fiber or the capacity of a single wavelength). Additionally, the number of wavelengths per link can be bounded by a maximum value.

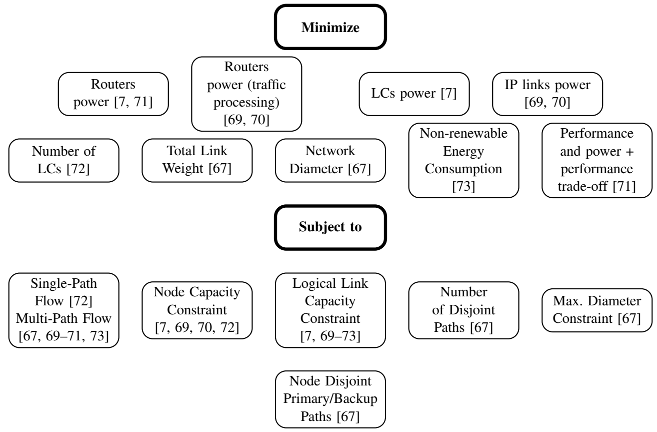


Fig. 4. MILP formulation for the Energy-Aware Network Design (EA-ND) – IP layer.

TABLE III: Energy-Aware Network Design (EA-ND) approaches targeting power saving in IP layer.

Method's Name, First author(s), Year of the first publication	Optical layer	Devices to install	Installation of fibers	Routing IP	Routing Optical	Wavelength conversion	Wavelength Assign.	QoS constraint	Computa-tion time	Protection considered
Routers and Other Devices targeted for power saving										
MILP [71], Sansò & Mellah 2009	n/c	Routers	n/c	MPR	n/c	n/c	n/c	consid.[5]	hours	no
MILP [7], Chabarek 2008	n/c	Routers, LCs	n/c	MPR	n/c	n/c	n/c	n/c	hours	no
LCs and Other Devices targeted for power saving										
MLTE [74–76], Puype 2009	WDM	LCs	n/c	SPR, ShPR with differently weighted links	n/c	n/c	n/c	n/c	hours	no
Start-SH&ReR [72], Coiro 2012	WDM	LCs	n/c	SPR, ShPR	n/c	n/c	n/c	n/c	n/r	no
MILP[6] [68], Lui 2013	WDM	LCs	no	SPR	ShPR	n/c	n/c	existence of non-sleep-enabled LCs	hours	non-sleep-enabled LCs carrying fraction of traffic
"Follow the Sun, Follow the Wind" MILP, Follow-Shuffle-X heuristic [73], Shen 2014	WDM	LCs, TSPs	n/c	MPR	n/c	n/c	n/c	n/c	Complexity analysis	no
Other Devices targeted for power saving										
MILP, LE-I, and GA [69, 70], Ahmad, Bianco & Bonetto 2010	WDM	transmitters and receivers	n/c	SPR (Dijkstra in LE-I and GA) and MPR (MILP)	n/c	n/c	n/c	n/c[7]	>24 hours (MILP), n/r (LE-I, GA)	no
ADD[8], DEL [67], Gebert 2014	n/c	IP links	n/c	MPR	n/c	n/c	n/c	n/c	n/r	SPP

[5]A MILP objective trading power against performance is considered in [71]. However, there is a mistake in the equation defining the objective (wrong units of mean delay in Eq. (7) of [71]).
[6]The MILP formulation is solved but it is not shown in [68].
[7]Number of hops analyzed in [70].
[8]Four approaches for creation of reduced topology graphs (input to the ADD) are considered in [67].

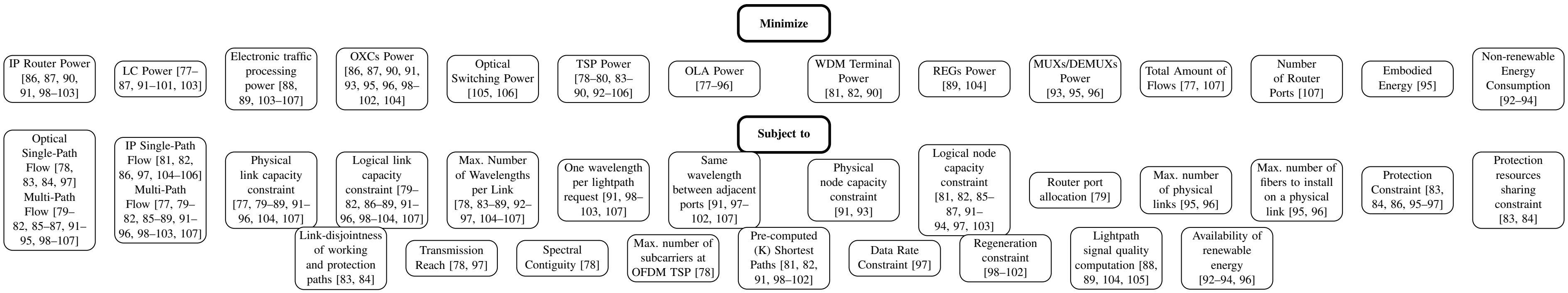


Fig. 5. MILP formulation for the Energy-Aware Network Design (EA-ND) – IP and optical layers.

TABLE IV: Energy-Aware Network Design (EA-ND) approaches targeting power saving in IP and optical layers.

Method's Name, First author(s), Year of the first publication	Optical layer	Devices to install	Installation of fibers	Routing IP	Routing Optical	Wavelength conversion	Wavelength Assign.	QoS constraint	Computa-tion time	Protection considered
Routers and Other Devices targeted for power saving										
P-EER and QA-EER [108], Fallahpour 2014	EON	IP routers, OXCs, TSPs, OLAs	no	n/a	SPR, ShPR power consumption values	at 3R REGs	FF	blocking	n/r	no
MILP [86, 87], Betker 2012	WDM	IP routers, LCs, TSPs, OXCs, OLAs, WDM terminals (fibers)	yes	SPR, MPR	MPR	n/c	n/c	over-prov.	hours	link disjoint paths
GA and ILP for CS and PS [90], Bianco 2013	WDM	IP routers, LCs, TSPs, OXCs, OLAs, WDM terminals	no	SPR (GA and ILP PS), single hop (GA and ILP CS)	SPR, ShPR power consumption of links (GA), SPR (ILP PS), MPR (ILP CS)	no	n/c	n/c	hours (ILP), minutes (GA)	no
DLH/IGH [109], Ahmad 2014	EON	IP routers, OXCs, TSPs, OLAs	no	n/r	SPR, ShPR geographical distance	n/c	FF	n/c	n/r	no
MILP [110], Palkopoulou 2009	WDM	IP routers, LCs, OXCs, TSPs	no	n/r	n/r	full	n/c	n/c	hours	no
MILPs for opaque, transparent, and translucent MLR networks [88, 89], Chowdhury 2010	WDM	IP routers, LCs, TSPs, OLAs, REGs	yes	MPR	MPR	full (transparent, translucent) or no (opaque)	consid.	n/c	hours	no
Composition approach (cost reduction RSA) [111–114], Klekamp 2010	WDM/ EON	IP routers, LCs, TSPs, OLAs, REGs, WDM shelves	yes	n/r	SPR, ShPR number of hops times bandwidth	at OEO	FF	n/c	n/r	no
MILP [98–101], Rizzelli 2012	WDM	IP routers, LCs, TSPs, REGs	no	MPR	MPR	no	consid.	n/c	hours	no
MILP (Bypass and Direct Bypass)[102], Rizzelli 2013	WDM	IP routers, LCs, TSPs, REGs	no	MPR	MPR	no	consid.	n/c	hours	no
2-step MILP [91], Wang 2011	WDM	IP routers, LCs, TSPs	yes	MPR	MPR	n/c	n/c	n/c	n/r	no

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TABLE IV Energy-Aware Network Design (EA-ND) methods targeting power saving in IP and optical layers – continued from previous page.

Method's Name, First author(s), Year of the first publication	Optical layer	Devices to install	Installation of fibers	Routing IP	Routing Optical	Wavelength conversion	Wavelength Assign.	QoS constraint	Computa-tion time	Protection considered
MILP [103], Shen 2012	WDM	IP routers, LCs, TSPs	no	MPR	MPR	n/c	consid.	over-prov.	hours	no
MILP [81, 82], Idzikowski 2013	WDM	IP routers, LCs, OLAs, WDM terminals (fibers)	yes	SPR, MPR	MPR	ppr	ppr	over-prov.	hours	no
GAGD (joint and two-step design) [82, 115], Bianco 2013	WDM	IP routers, LCs, OLAs, WDM terminals (fibers)	yes	SPR, MPR	MPR	n/c	n/c	over-prov.	mins.	no
LCs and Other Devices targeted for power saving										
MILP for basic, transparent and translucent networks [104, 106, 116, 117], Vismara & Musumeci 2010	WDM	LCs, OXCs, TSPs, REGs	no	SPR	MPR	at 3R REGs	consid.	n/c	hours	no
TDS [105, 106], Musumeci 2011	WDM	LCs, TSPs, OXCs, REGs	no	SPR	MPR	at 3R REGs	consid.	no	n/r	no
ILP and heuristic REO-hop for networks with renewable energy sources [92–94, 118], Dong 2010	WDM	LCs, TSPs, OXCs, OLAs	yes	MPR (ILP), SPR (REO-hop)	MPR (ILP), SPR (REO-hop)	full	n/c	n/c	hours	no
MILP-Power minimized physical topology optimization [96] (renewable energy) [95] (embodied energy), Dong 2012	WDM	LCs, TSPs, OXCs, OLAs	yes	MPR	MPR	full	n/c	n/c	hours	min. nodal degree 2
MILP, direct bypass, multi-hop bypass [85], Shen & Tucker 2009	WDM	LCs, TSPs, OLAs	yes	SPR (direct bypass, multi-hop bypass) and MPR (MILP)	MPR	full	n/c	n/c	hours	no
ILP for PA design of protected networks [83, 84], Musumeci 2012	WDM	LCs, TSPs, OLAs	no	n/c	SPR	n/c	n/c	n/c	hours	SLP, SPP, DLP, DPP
MILP, linear relaxation of the MILP [80], Lui 2012	WDM	LCs, TSPs, OLAs	yes	MPR	MPR	n/c	n/c	n/c	n/r	no
MILP-Power minimized, MILP-Spectrum minimized [78], Dong 2013	EON	LCs, TSPs, OLAs	no	n/r	n/r	n/c	FF	no	hours	no
SSGPE, MSGPE [119], Hou 2013	EON	LCs, TSPs, OLAs	no	SPR, ShPR hop count	SPR, ShPR hop count[9]	Allowed at OEO	FF	no	complexity analysis	DPP
Joint MILP, Detached MILP, Reconfigurable and Fixed Split Ratio Joint MILP [79], Lui 2013	WDM	LCs, TSPs, OLAs	yes	MPR	MPR	no	part of MILP	no	complexity analysis	no
Multi-hop bypass [85] with sequential router-port allocation or interleaving router-port allocation [79], Lui 2013	WDM	LCs, TSPs, OLAs	yes	MPR	SPR (direct bypass, multi-hop bypass)	no	n/c	no	n/r	no
MILP [107], Yetginer 2009	WDM	LCs, TSPs	no	MPR	MPR	n/r	consid	over-prov.	hours	no
MXHF [120], Hou 2012	WDM	LCs, TSPs	no	n/r	MPR	at OEO	consid.	max IP hop	n/r	no
MILP [77], Lee 2012	WDM	LCs, OLAs	no	MPR	MPR	n/c	n/c	overprov.	n/r	no
ILP [97], Perelló 2014	EON	LCs, TSPs	no	SPR, ShPR hop count	SPR, ShPR geographical distance	n/c	FF	over-prov.	hours	shared, restoration
HCTG, HOCTG [121], Lee 2014	WDM	LCs, OLAs	no	SPR	SPR	n/c	n/c	overprov.	n/r	no
E2SR [122], Zhang 2014	EON	LCs, TSPs	no	SPR, ShPR power consumption	SPR, ShPR geographical distance	Allowed at OEO	FF	no	n/r	DPP 1:N (1:2)

[9]Based on complexity analysis shown in the last paragraph of Section 3 of [119], and not the example provided in Fig. 2 of [119].

Each lightpath request has to be mapped on a wavelength. Furthermore, the same wavelength has to be used between adjacent ports. Node capacity can be bounded by a maximum capacity for the physical nodes as well as for the logical ones. Moreover, a constraint governing the allocation of ports on LCs can be inserted in order to avoid multiple LCs containing both active and inactive ports used to realize a logical link consisting of multiple lightpaths.

In general, the number of available resources to install may be limited. Therefore, constraints on the maximum number of fibers per link and on the maximum number of physical links can be introduced. Moreover, protection of traffic demands might be considered during the design phase (i.e., by reserving for example an additional amount of bandwidth on each link, by introducing also a constraint on resource sharing and/or requiring link-disjointness for working and protection paths).

Physical constraints such as the transmission reach (maximum distance that a signal can travel before it degrades to a level that needs to be regenerated) can be included. Furthermore, the introduction of EON may require some other constraints to be considered. For instance the spectral contiguity (i.e., the spectral resources for a super-channel must be assigned in a contiguous manner), or the maximum number of subcarriers at Orthogonal Frequency Division Multiplexing (OFDM) TSP (i.e., the BV-TSP may have an upper limit on the number of subcarriers that it is able to deal with). Eventually, the routing can be also constrained to follow specific paths which are pre-computed.

When the device admits different data rates, a constraint for setting a single data rate of lightpaths and TSPs should be introduced. Moreover, a constraint limiting the regeneration can be taken into account. Finally, more specific constraints, such as the computation of the signal quality, or the fact that some energy can be derived from renewable sources, are sometimes used.

2) Comparison of Approaches: Table IV reports the main characteristics of the algorithms. In particular, we have differentiated among the following categories: (1) IP routers and other devices, and (2) LCs and other devices.

Routers and Other Devices: This category covers IP routers together with LCs, TSPs, OXCs, OLAs, WDM terminals, REGs, and WDM shelves. Most of the works assume WDM rather than the relatively new EON. Installation of fibers is considered in roughly half of the works. Focusing then on routing, it is generally taken into account in both layers. Moreover, most of the works consider MPR for IP and optical layers. This is due to the fact that in general the MPR guarantees more flexibility when the traffic demands are split over several paths. Similar to the optical design phase, wavelength conversion may be fully allowed. Moreover, wavelength assignment is not carried out in several approaches. However, we point out that this is a minor issue, since wavelength assignment can be performed even in a post-processing step. Focusing then on QoS constraint, different works assume overprovisioning. However, if the design phase is then followed by an EA-NO approach, it is important to keep the same metrics for evaluating the QoS, i.e., the network should guarantee the same level of QoS. Focusing on computation time, the surveyed approaches require even hours to retrieve a solution. However, the computation time is not a stringent constraint, since the design phase is normally performed off-line. Finally, focusing on protection, it is generally not applied in most of the current works (except for the MILP formulation in [86, 87]). This is a major drawback of current approaches, and it should be analyzed in more detail in future works, in order to prevent the negative effects of failure events during network operation.

LCs and Other Devices: We then consider approaches targeting LCs together with TSPs, OXCs, REGs, and OLAs for power saving. Similarly to the previous category, the impact of the EON has been preliminarily investigated by only a few recent works, thus posing the way for further research in this direction. The installation of fibers is considered by six approaches. Focusing then on routing, current works tend to exploit both layers (either with SPR or with MPR). Similarly to the previous category, wavelength conversion and wavelength assignment are not strict constraints. The impact in terms of QoS is not taken into account in the majority of works, and must be carefully considered in the future. In particular, the designed network should guarantee the required QoS in the network during the operation phase. Additionally, the presented approaches may require hours to obtain a solution. However, as mentioned before, this is a minor issue during the design phase. Finally, regarding protection, we can see that it is considered in different works. This is actually in clear contrast with the previous category (i.e., when IP routers together with other devices are considered), due to the fact that, when routers are considered, an additional level of complexity is introduced.

IV. Energy-Aware Network Operation

Taxonomy used for the EA-NO approaches is presented first. Then, we classify the EA-NO approaches according to the layers that they target to save energy. First, the methods targeting separately the optical and IP layers are described. Next, we present the methods targeting jointly the IP and optical layers. Similarly to the EA-ND, we consider the devices targeted during the execution of the algorithm as the main criterion to classify the approaches to the corresponding layer(s).

We proceed for each layer in the following way. We first provide a scheme of the problem formulation, and then we provide a comparison of the EA-NO approaches together with a table summarizing their main features.

A. Taxonomy

There are fewer decisions (variables) to make during network operation than in the network design. However, there are more constraints with respect to the network design. This is reflected in the taxonomy [123]. The main criterion for classification are the **devices targeted for switching on/off**. Second, the **dynamics of routing** is distinguished, i.e., whether routing in the optical layer, in the IP layer or in both layers can be dynamically changed. This influences complexity of an EA-NO approach as well as the actual network reconfiguration determined by the EA-NO approach. Similarly as in Section III-A, **routing in the optical layer** and **routing in the IP layer** are reported. The main difference with respect to the network design is the requirement to mind the **constraints on the installed devices**, i.e., LCs, fibers, OLAs and other network devices must not be installed in the network during its operation. On the other hand, energy saving is usually traded with **QoS**. Its consideration by the EA-NO approach is another item in the taxonomy.

The **computation time** of the energy-efficient network configuration is crucial in the context of dynamically changing traffic. We focus on network topologies of up to 40 nodes in case results on topologies with more nodes are reported, due to the fact that larger topologies most probably include metro/access networks additionally to the core network. The reported computation values are only indicative. Fair comparison would require testing the EA-NO approaches over the same network scenario and with the same methodology (simulation framework, etc.). Other aspects to consider are the **triggering events** for timely launching the EA-NO approaches.

Operation of the network can be either centralized or distributed. Any EA-NO approach can be centrally operated assuming that there are mechanisms delivering input information, and control mechanisms distributing the computed solution. Distributed approaches are more challenging, since they normally require a higher amount of exchanged information between nodes. In this work, we report centralized network operation of each EA-NO approach, unless distributed operation is clearly indicated in the corresponding publication. **Network knowledge** determines the information that is required by the EA-NO approach, and is classified as either local or global. It is obvious that it is easier and quicker to run an EA-NO algorithm that requires only the knowledge about the traffic load on local links than the other one requiring a full Traffic Matrix (TM).

Apart from the QoS, the energy saving is traded also with the level of **protection** against network failures. Therefore protection is also considered in this survey, even though many operators run two networks in parallel [124], and the EA-NO approach may be applied to the secondary network only, while the primary one is operated at full speed.

While adapting the network to the changing traffic conditions may bring energy savings, the network needs to be reconfigured between consecutive time periods. In this context, it is important to keep the **reconfiguration cost** (in terms of added/deleted lightpaths or rerouted traffic) to a limited extent.

While theoretical studies can show high potentials of energy savings, the **knowledge of future traffic** is crucial in order to achieve the savings. Although it is obvious that nobody knows future traffic, many works neglect the restriction that is related to the (short-term) traffic forecast.

Eventually, the **control mechanisms** to deliver the required input information for the EA-NO approach as well as to perform the actual reconfiguration are necessary.

Some of the criteria can be neglected when looking at single layers. **Optical layer:** Routing mechanism and its dynamics in the IP layer are not considered by the EA-NO approaches working only in the optical layer.

IP layer: Routing mechanism and its dynamics in the optical layer, as well as the physical layer constraints are usually not considered by the EA-NO approaches working only in the IP layer.

Furthermore, different targeted devices, QoS metrics, triggering events, reconfiguration costs are applicable in the two layers.

B. Optical layer

We describe the formulation of the problem in Section IV-B1, while the comparison of the surveyed approaches is reported in Section IV-B2.

1) Formulation: The problem formulation is reported in Fig. 6. The objective function consists of minimizing the power consumption of active optical devices, focusing on OXCs, TSPs, OLAs, and REGs or even more detailed (sub)components, namely MEMSs, TXs, and RXs. Moreover, a complementary term to the device power consumption is the number of used OXC ports, i.e., the ports that are actually activated to satisfy a given traffic demand. Finally, a second term in the objective function may be the number of lightpaths below a given signal quality threshold or the number

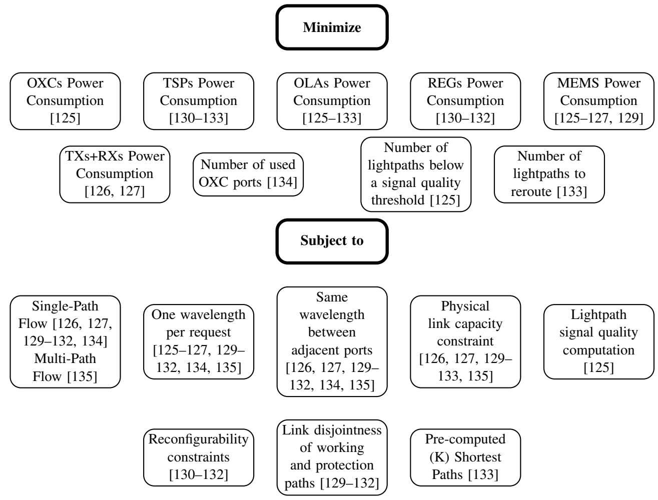


Fig. 6. MILP formulation for the Energy-Aware Network Operation (EA-NO) – optical layer.

of lighpaths that need to be rerouted, which should be properly weighted with a parameter.

Focusing on the constraints, the traffic has to be routed in the network (using single or multiple paths). Moreover, at least one wavelength should be reserved for each traffic request, and wavelength continuity should be taken into account between adjacent ports. Additionally, the link load should not exceed the maximum physical link capacity. In case the objective function includes the signal quality threshold, a constraint to compute the signal quality has to be inserted. Moreover, a constraint on reconfigurability of the optical layer may be considered (e.g., in the case of limited reconfigurability, offered traffic demands in low-traffic periods are transported with a subset of the lightpaths to be established for the peak traffic load). Focusing then on protection, link disjointness between working and protection paths may be requested. Finally, the selected paths may be chosen from a set of pre-computed paths (e.g., one used path between a source node and a target node out of K-Shortest Paths (KShP)).

2) Comparison of Approaches: Table V reports the main features of the approaches, differentiating between the targeted devices. In particular, the approaches reported in Table V are ordered according to the following categories of targeted devices: (1) OXCs and other devices, and (2) other devices.

OXCs and Other Devices: In this category all approaches targeting OXCs (together with TSPs, OLAs, REGs, and WLCT) are considered. The first outcome of Table V is that few works consider EON. This aspect, mainly due to the recent development of EON technology, suggests investigation of new algorithms for such a scenario as a future research topic.

Routing is considered only at the optical layer, since the IP routing has a limited impact on the status of optical devices. MPR is never used (even in the MILP [125]). The routing strategy is most commonly a ShPR, using power consumption as link weights.

TABLE V: Energy-Aware Network Operation (EA-NO) approaches targeting power saving in optical layer.

Method's Name, First author(s), Year of the first publication	Optical layer	Targeted Devices	Dynamics of routing	Routing IP	Routing Optical	Physical layer constraints	Constraints on installed devices	Impact on QoS	Computation time	Triggering events	Operation	Network knowl.	Protection consid.	Reconfiguration cost	Future traffic assumption	Control mechanisms
OXCs and Other Devices targeted for power saving																
MP-S [136], Monti 2011	WDM	OXCs, TSPs, OLAs, WLCTs	optical	n/c	SPR, ShPR	wavelength conversion	included	no	n/r	arrival of lightpath request	centr.	global	DPP 1:1	no reconfiguration	unknown	n/c
EA-DPP-Dif, EA-DPP-MixS, EA-DPP[10] [137], Jirattigalachote 2011	WDM	OXCs, TSPs, OLAs	optical	n/c	SPR[11]	consid. (WA)	included	no[12]	n/r	arrival of lightpath request	centr.	global	DPP with disjoint paths	n/c	unknown	n/c
WPA-LR [138], Wiatr 2012	WDM	OXCs, TSPs, OLAs	optical	n/c	one of 3-shortest paths[13]	consid. (WA)	included	wavelength usage	n/r	arrival & termination of lightpath requests	distr.	global	no	n/c	unknown	n/c
MILP [125], Çavdar 2012	WDM	OXCs, TSPs, OLAs	optical	n/c	SPR, ShPR	lightpath signal quality	n/c	signal quality threshold	n/r	arrival & termination of lightpath requests	centr.	global	no	n/c	unknown	n/c
SPP-based DiR [139], Muhammad 2013	WDM	OXCs, TSPs, OLAs, REGs	optical	n/c	SPR, KShP	consid. (WA)	included	differentiated traffic	n/r	arrival & termination of lightpath request	centr.	global	SPP	no reconfiguration	known	n/c
SM/ASM [140, 141], Tafani 2012	WDM	OXCs, TSPs, OLAs, WLCTs	optical	n/c	SPR	consid. (WA)	n/c	overprov.	n/r	exceeding util. thresholds	distr.	local	no	n/c	unknown	Sleep Mode Signaling
PASPP [142], Bao 2012	WDM	OXCs, TSPs, OLAs, WLCTs	optical	n/c	SPR, ShPR with link occupancy	consid. (WA)	n/c	wavelength usage	complexity analysis	flow arrival, termination of lightpath request	centr.	global	SPP	n/c	unknown	n/c
Dynamic EA-RWA, Dynamic EA-RMLSA [50, 143], López Vizcaíno 2012	WDM or EON	OXCs, TSPs	optical	n/c	SPR, ShPR with power consumption values	WA, lightpath length, channel allocation, modulation format	included (OLAs, fibers)	n/c	secs.	flow arrival, termination of lightpath request, traffic change	centr.	global	no	n/c	unknown	n/c
DP TAPA [53, 144], López Vizcaíno 2012	WDM or EON	OXCs, TSPs	optical	n/c	SPR, ShPR with power consumption values	WA, lightpath length, channel allocation, modulation format	included (TSPs, OXCs, OLAs, fibers)	n/c	secs.	traffic change	centr.	global	DPP 1+1	n/c	known	n/c
Diff QoP for Dynamic EA-RMLSA [145], López Vizcaíno 2013	EON	OXCs, TSPs	optical	n/c	SPR, ShPR with power consumption values	WA, lightpath length, channel allocation, modulation format	included (OLAs, fibers)	n/c	secs.	flow arrival, termination of lightpath request, traffic change	centr.	global	SPP, DPP 1+1, DPP 1:1	n/c	unknown	n/c

Continued on next page

[10]Different assignment of weights (costs) to links is used in EA-DPP-Dif, EA-DPP-MixS, EA-DPP [137].
[11]Link weights (costs) are assigned in [137].
[12]Blocking probability is analyzed in [137] and [135].
[13]Each fiber link is assigned a weight dependent on power of OLAs on the link and whether the link is in use [138].

TABLE V Energy-Aware Network Operation (EA-NO) approaches targeting power saving in optical layer – continued from previous page.

Method's Name, First author(s), Year of the first publication	Optical layer	Targeted Devices	Dynamics of routing	Routing IP	Routing Optical	Physical layer constraints	Constraints on installed devices	Impact on QoS	Computation time	Triggering events	Operation	Network knowl.	Protection consid.	Reconfiguration cost	Future traffic assumption	Control mechanisms
ISFO [129, 146], Coiro 2011	WDM	OXCs[14], OLAs[15]	optical	n/c	SPR with power consumption values	consid. (WA)	included	n/c	n/r	traffic increase	distr.	global	SPP	n/c	known	n/c
Green Spark [147], Ricciardi 2012	WDM	OXCs, OLAs, REGs	optical	n/c	SPR	wavelength conversion	n/c	wavelength usage	complexity analysis	flow arrival	distr.	global	no	n/c	unknown	GMPLS extension
Other Devices targeted for power saving																
MILP with Connectivity Graph [130–132], Morea & Perelló 2013	WDM	TSPs, OLAs, REGs	optical	n/c	SPR	consid. (WA, lightpath length)	included	wavelength usage	n/r	arrival & termination of lightpath requests	distr.	global	Dedicated 1:1	n/c	known	GMPLS extension
Datarate adaptation [148], Morea 2013	EON	TSPs, REGs	optical	n/c	SPR, ShPR geographical distance	WA, lightpath length, channel allocation, modulation format	included (TSPs, REGs)	overprov.	n/r	change of traffic demand	centr.	global	DPP 1+1	n/c	known	n/c
SMA-GMPLS, ILP [133, 149], Cerruti 2010	WDM	TSPs, OLAs	optical	n/c	SPR, KShP	WA	included	overpr., wavelength usage	n/r	exceeding util. thresholds	distr. (SMA), centr. (ILP)	global	no	rerouted traffic	known	make-before-break
DON (ShP-FF, 3-ShP-FF, AUR-E) [150, 151], Leiva 2010	WDM	TSPs (including WLCTs)	optical	n/c	SPR	wavelength conver.	included	max. allowed block. prob.	n/r	arrival & termination of lightpath requests	centr.	global	no	n/c	known	GMPLS, ASON
LBG [152, 153], Farahmand 2011, Hasan 2012	WDM	TSPs	optical	n/c	SPR, ShPR	WA	included	wavelength usage	n/r	arrival & termination of lightpath requests	centr.	global	no	no reconfiguration	unknown	n/c
TAP-BR [154], Zhang 2012	EON	TSPs, ports	optical	n/c	SPR, ShPR geographical distance and index to exploit grooming	WA, lightpath length, channel allocation	n/c	blocking	n/r	flow arrival, termination of lightpath request	centr.	global	no	n/c	known	n/c
PA-RWA (LBC and LCW) [128, 135, 155], Coiro 2011	WDM	OLAs	optical	n/c	SPR[16]	consid. (WA)	included	no[12]	subsecs.	timer	distr.	global	no	n/c	unknown	n/c
RWA-Bill ILP [126, 127], Çavdar 2011	WDM	OLAs	optical	n/c	SPR	consid. (WA)	included	n/c	hours	timer (every hour)	centr.	global	no	n/c	known	GMPLS extension
CPEEM/CPSPM [134], Hou 2011	WDM	ports	optical	n/c	SPR	wavelength conversion	n/c	wavelength usage	complexity analysis	flow arrival	centr.	global	no	n/c	unknown	n/c

[14]MEMS-based switching matrix used in [129, 146].
[15]In-line, pre- and post-amplifiers are considered in [129, 146].
[16]LBC with time variant link weights [128, 135, 155].

The main physical layer constraint taken into account is wavelength continuity requiring a wavelength assignment procedure. Only Minimum Power with Sleep mode support (MP-S) [136] and Green Spark [147] consider the availability of wavelength converters. The availability of commercial wavelength converters is still an open issue. In the case of EON, the routing algorithms also have to consider channel allocation and modulation format, making the overall routing problem more complex. Most but not all approaches consider the constraint on installed devices. This constraint is critical for all the EA-NO approaches, and has to be considered in future works.

Half of the works evaluate the impact on QoS (mainly by considering the wavelength usage as a reference parameter). An unexpected outcome is that computation time is rarely reported. This feature should be investigated more in depth, since time may become a strict constraint when the proposed approach is applied in a realistic scenario.

A large part of the approaches use a dynamic scenario, where the triggering event is the arrival or termination of a traffic demand. Only few works consider other events, i.e., traffic change or the exceeding of a utilization threshold. However, these events need to be carefully managed to avoid the case in which the EA-NO algorithm is run too frequently (leading to a frequent variation of the device power state) or too rarely (i.e., thus not promptly reacting to traffic variation).

Most of the reported approaches are based on a centralized implementation with a global network knowledge. In this way the presence of a central control element running the algorithm and managing the power state for all devices is required. Protection schemes are taken into account by many approaches, with both shared and dedicated schemes.

Focusing then on reconfiguration costs, we have surprisingly found that this aspect is rarely considered. However, changing frequently the set of powered devices (especially when the algorithm is run for each request), may negatively impact the reliability of network components as well as the QoS perceived by users due to traffic shifting between devices. Thus, we stress the fact that reconfiguration costs should be taken into account in this context.

Future traffic is assumed to be unknown in most of the works. Finally, regarding the adopted control mechanisms, only two works consider them (Sleep Mode Signaling used in Sleep Mode (SM)/Adaptive Sleep Mode (ASM) [140, 141] and Generalized MultiProtocol Label Switching (GMPLS) extensions used in Green Spark [147]). This aspect should be further investigated, since a centralized approach with a global network knowledge requires a control mechanism to exchange information in the network.

Other Devices: This category gathers optical operational approaches not considering OXCs as targeted devices. In particular works exploiting the low power states of TSPs, OLAs and REGs are reported.

There are very few differences with respect to the analysis of the OXCs-related approaches. The first one is that in this case also geographical distance is considered as link weight when ShPR is used. The main reason is that when TSPs and REGs are the targeted devices, physical distance of optical links becomes a limiting factor to efficiently establish lightpaths.

A further outcome is related to protection. It is taken into account only by the MILP with Connectivity Graph [130–132] and the datarate adaptation approach [148]. Considering that these two approaches are also the most recent ones, we believe that this aspect is mainly due to the ”higher age” of the considered approaches with respect to the OXCs-related ones. The inclusion of protection schemes into the energy aware routing problem, proposed for the first time in some works from 2011, is a standard feature of all works proposed from 2013 onwards.

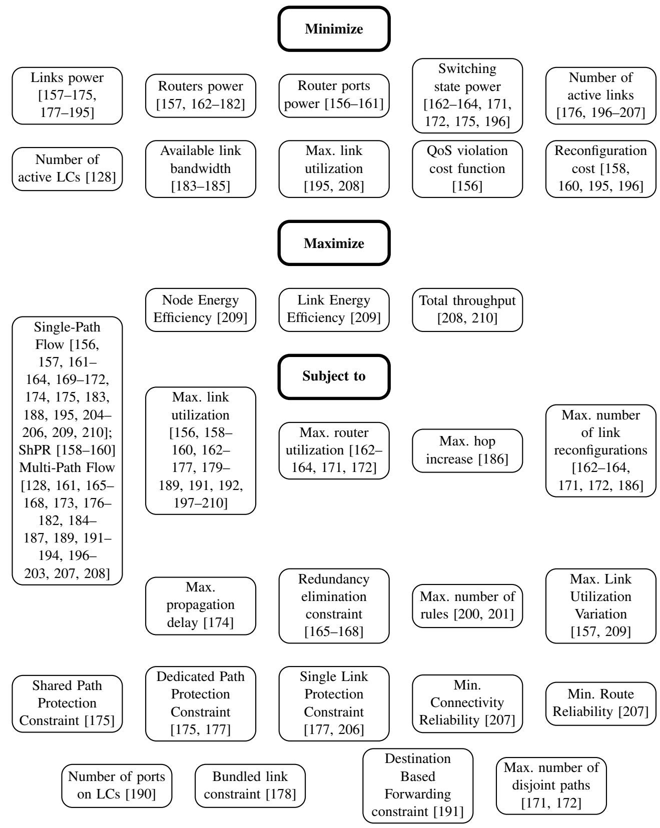


Fig. 7. MILP formulation for the Energy-Aware Network Operation (EA-NO) – IP layer.

C. IP layer

Section IV-C1 details the problem formulation, while Section IV-C2 presents the comparison of the surveyed approaches.

1) Formulation: We focus on the definition of the problem as an optimization model. Fig. 7 reports the main objective functions and constraints adopted to formalize the problem across the existing works.

Considering first the objective function, most of the works minimize power consumption of active links (mainly in terms of LCs) and eventually of active nodes (i.e., entire routers or their parts). Additionally, some works target minimization of the power consumption of router ports, thus assuming that a single LC can partially put into sleep mode a subset of its ports. As a second term of the objective function, power consumption incurred when switching from one state (e.g., full power) to another one (e.g., sleep mode) may be considered. This is due to the fact that power state transitions may temporarily increase device's power consumption, and therefore it is important to limit their occurrences. Moreover, different works minimize the number of active links or LCs rather than their power consumption. This objective is mutual compared to the power consumption of active links and it is particular effective in the case in which all the links exhibit similar consumption at full power. Interestingly, we have not found any work minimizing solely the number of active nodes.

A complementary objective function may be the minimization of the available link bandwidth, i.e., to select the set of links in active state so that their capacity is sufficient to satisfy the traffic demands. Additionally, the minimization of the maximum link utilization (either as a single objective or a weighted term) may be pursued, although this objective might not find the subset of devices guaranteeing the highest energy-saving. Moreover, a QoS violation cost function should be introduced to consider the case in which for example links may be filled beyond the maximum allowed value (not beyond their capacity). Finally, the cost introduced when a device is reconfigured can be inserted as an additional term, often referred as reconfiguration cost. This cost can be expressed for example in terms of traffic that needs to be shifted from a device that is going to be powered off to other devices or in terms of number of power state reconfigurations which may limit the devices' reliability.

Another possible objective function (which is supposed to replace the power consumption of active devices) is the maximization of nodes and links energy efficiency (expressed in terms of power over capacity). Finally, the maximization of the total throughput may be considered as objective function (although this objective might not find the most energy-efficient solution).

Looking at the constraints, the traffic has to be routed in the network (via single or multiple paths). Additionally, a constraint limiting the maximum link utilization has to be inserted in order to avoid overload on one hand and to provide some spare capacity for unpredicted traffic on the other hand. Moreover, works targeting power consumption of active routers may also consider the maximum utilization of routers in order not to exceed the routers capacity. When the device utilization constraint is introduced, a fraction of the "unused" capacity is assumed with respect to the forecasted traffic, in order to provide an amount of overprovisioning in the network for the actual traffic. Additionally, the maximum hop increase can be taken as a constraint, i.e., to avoid the case in which all or some traffic demands have to traverse many nodes toward their target nodes as too many links are powered off.

Considering then the power state configurations, different works impose a maximum number of link reconfigurations, in order to: (1) reduce the amount of traffic that is rerouted when the network is reconfigured after a change of the TM, (2) limit the impact on the device reliability introduced by frequent power state transitions. Another constraint is the maximum propagation delay, which may increase after the sleep modes are applied, especially in the case in which long-haul links are taken into account.

Moreover, there are other constraints that are specific to the technology which is assumed. In particular, the redundancy elimination may be considered. This technique decreases the link load of links by merging traffic to the same destination (e.g., a video content server) which is shared on the same link. In such a case, a redundancy elimination constraint should be introduced. Additionally, when SDN nodes are taken into account, the maximum number of rules on each SDN node may be bounded.

Focusing then on the scenario of time-varying demands, a constraint limiting the maximum variation of link utilization may be introduced, i.e., to avoid the case in which a large amount of traffic is shifted from the links in the network as a consequence of a TM change.

Interestingly, we have found few works considering protection and reliability constraints in the formulation. This is due to the fact that these constraints impose more complex formulations which are difficult to be optimally solved, and therefore heuristic approaches are preferred. Focusing on protection, alternative paths have to be found when a failure occurs. These paths may be shared with the paths used in normal operation (i.e., without failure) or may be dedicated. In general, protection is imposed by assuming the failure of a single link, and therefore introducing a new set of constraints. Focusing then on reliability, both connectivity or route reliability may be inserted in the constraints [207]. The connectivity reliability[17] is defined as the probability that a link (and corresponding devices such as LCs and TSPs) on a path is available. Similarly, the route reliability is defined as the probability that the entire path between a given source node and a given target node is available. Both of them should be bounded by a maximum value.

A constraint ensuring sufficient number of ports on active LCs needs to be inserted in case multiple ports on a LC are distinguished requiring port allocation to established lightpaths (similarly to [79] as reported in Section III-D1). All ports on inactive LCs must not be used.

Moreover, if the physical connection is formed by a bundled link, a constraint may be introduced to power off the whole or only part of the bundle. Additionally, a constraint which forces a router to use a specific destination should be introduced if Destination Based Forwarding (DBF) is taken into account.

Finally, the maximum number of disjoint paths may be introduced, i.e., to avoid the case in which a single demand is split across several paths introducing negative effects such as packet reordering if the packets do not arrive in the same order as they are sent.

2) Comparison of Approaches: Table VI reports the main characteristics of the approaches. We consider the following categories of approaches: (1) routers, (2) routers and other devices, (3) LCs and other devices, (4) LCs, and (5) other devices. We then report a comparison of the approaches for each category.

Routers: We first consider approaches targeting solely the power consumption of routers. In this case, the routing is only in the IP layer (either SPR or MPR). Consequently, the routing at the optical layer and the physical layer constraints are not considered. In general, all the approaches include the constraint on the installed devices, which is a mandatory requirement (i.e., the algorithm should not require to install new devices in the network). The impact on QoS is handled by means of overprovisioning, a threshold on the link load, or by means of a specific metric. Computation time is not reported. This constraint should be carefully considered by future works due to the fact that changing the router power state is a complex task, which may require additional time to be performed after the time required to retrieve a solution. Focusing on triggering events, they are not reported in most of the works. This is also a feature that should be fully considered toward the implementation of the algorithms in real networks. The operation is centralized or distributed, although current trends (especially considering SDN management) push toward the implementation of centralized approaches. Moreover, the network knowledge is global in all of the approaches. This is a reasonable constraint, as turning off a node may impact other nodes in the topology, and therefore the turning off decision has to consider the global knowledge of the network. Astonishingly, protection is not considered. This is also a point which is of mandatory investigation for future works. In particular, approaches targeting routers should always guarantee backup paths for demands, in order to quickly react to

[17]The term "Terminal Reliability (TR)" and not "Connectivity Reliability" is used in [207]. The term "Terminal" relates to a target node, and TR determines reliability of any operational path between a source and a target node.

failure events. Focusing then on reconfiguration costs, they are not considered at all. This is also a major drawback of current approaches, due to the following reasons: (1) routers require a non-negligible amount of time to boot up the operating system, (2) routers are in generally designed to be always powered on, and their activation/deactivation may increase their failure rate [211], and (3) the traffic has to be rerouted from the routers that are going to be powered off to the routers that remain powered on, thus potentially impacting the QoS. Focusing then on future traffic assumption, it is assumed to be either known or unknown in the surveyed works. An unknown traffic assumption is the most reasonable one, as forecasting future traffic is challenging in a real network. Finally, focusing on control mechanisms, they are generally not considered (except for the ad hoc mechanism introduced in the General Distributed Routing Protocol for Power Saving (GDRP-PS) [212]). Since the proposed approaches consider the global state of the network, defining a control mechanism (and possibly adopting already available protocols) is of mandatory importance.

Routers and Other Devices: We then consider approaches targeting routers together with LCs, TSPs, and IP links (in general). When a node is turned off, all of its incident links are not used any more. Thus, it is straightforward to put into sleep mode the devices forming these links. Focusing on the layer, most of the approaches target the IP (except for [157] which considers also Synchronous Digital Hierarchy (SDH)). This is a reasonable assumption, as the LCs and IP links power state can be controlled by acting solely on the IP layer. As a consequence, the routing dynamics is IP with SPR being the predominant choice. Moreover, physical layer constraints and optical routing are not considered (as expected). In general, the constraint on the installed devices is always ensured. This is a mandatory constraint, in order to avoid the case in which more devices than the ones installed are required by the algorithm. Focusing then on QoS, it is ensured by imposing a maximum link utilization constraint, normally with an overprovisioning factor. This constraint is of mandatory importance for future work. However, we believe that it should be coupled with more stringent constraints, like the maximum increase in the number of path hops and the packet delay. Focusing then on computation time, we can see that it varies from ms to hours, or it is not reported at all. We believe that future works should carefully consider this aspect, since changing the power state for the considered devices will require a prompt reaction to the triggering events, which will be likely the TM change (as considered by most of the surveyed work). Similarly to the routers category, the operation is centralized and global knowledge is assumed. Astonishingly, protection is rarely considered. We believe that this aspect should be taken into account by future works. Focusing on reconfiguration costs, they are not considered by most of the surveyed approaches, thus triggering the need for future investigations. Moreover, the future traffic is assumed to be known by most works, which in turn limit the applicability of the proposed approaches in a real scenario. Finally, the control mechanism are rarely considered, being only LNH_solve [157] utilizing the ECONET framework [213, 214] and Energy-Efficient Multi Constrained Routing Algorithm (E2-MCRA) [215] exploiting MultiProtocol Label Switching (MPLS). Also in this case, future works are required to properly address this aspect.

LCs and other devices: In the following, we consider approaches which assume that the routers in the topology are always powered on. This seems a reasonable assumption, since in general turning off a link (or some of its components) is a less complex task than turning off an entire node. In this case, a few works assume WDM as the optical layer. Thus, devices from the optical layer, like TSPs, are considered with LCs. Additionally, the dynamics of routing may consider only the IP layer or also the changes in the LT. Focusing on IP routing, different works assume ShPR, thus guaranteeing not only connectivity between source and target nodes, but also the minimum number of hops between them. The routing in the optical layer is rarely considered, due the fact that, when the optical layer is considered, it is sufficient to solve the Logical Topology Design (LTD) problem. In addition, a subset of works consider the physical layer constraints, e.g., ensuring a maximum lightpath length. Similarly to the previous categories, we expect that all future works will consider the constraints on the installed devices. Focusing on the impact on the QoS, it is in general ensured by means of the overprovisioning constraint, although more realistic assumptions (like the increase in the number of traversed hops) should be introduced. The table reports then the comparison of the approaches in terms of computation time. Interestingly, different approaches report computation time in the order of seconds, thus being able to quickly react to sudden traffic variations. Focusing then on the triggering events, they are more diverse compared to the other categories of devices. In particular, such events can be mainly classified in the following strategies: (1) a variation of the traffic demands, (2) a variation of the utilization on the devices, and (3) the expiration of a timer. We believe that the most effective solutions are (1) and (2), since finding a good trade-off for setting a timer may be a challenge in real deployment. The operation of the proposed approaches can be either distributed (i.e., each node manages the set of its incident links) or centralized at a single control node. Moreover, the network knowledge is required to be global. To the best of our knowledge, only One-Hop/Conservative Setup (OH/CS), One-Hop/Aggressive Setup (OH/AS), Multi-Hop/Successive One Hop (MH/SOH), Multi-Hop/SinkTree (MH/ST) [216], and Fixed Upper Fixed Lower (FUFL) [193, 194, 217, 218] use local network knowledge. As in the previous categories, protection is rarely considered in the reported approaches. Interestingly, most of the approaches take into account reconfiguration costs. Additionally, a limited number of approaches consider the future traffic to be unknown (which is a realistic assumption), while in general control mechanisms are well exploited.

LCs: This category analyzes approaches targeting solely power consumption of LCs. Accordingly, the optical layer is not considered (apart from the Switch-On and Switch-Off MILPs [158–160] considering pre-computed WDM routing). The routing is dynamic in the IP layer rather than in the optical layer, with a predominant amount of approaches exploiting SPR. As expected, the physical layer constraints are not considered at all, while the constraints on the installed devices are generally included. Focusing on the impact on QoS, it is normally ensured by means of the standard overprovisioning. As in the previous categories, we envision more approaches targeting more detailed constraints to guarantee acceptable QoS levels by limiting the path length or the potential packet delays. The computation time is barely reported in the proposed approaches. This major drawback should be addressed in future works. Focusing then on the triggering events, they can be quite diverse in this category, including: (1) a traffic variation, (2) exceeding link utilization thresholds, (3) expiration of a timer, (4) arrival of a Link State Advertisement (LSA), (5) operator's decision. We believe that future EA-NO approaches should be triggered by multiple types of events, i.e., primarily upon exceeding of utilization threshold, and secondarily when a timer expires.

TABLE VI: Energy-Aware Network Operation (EA-NO) approaches targeting power saving in IP layer.

Method's Name, First author(s), Year of the first publication	Optical layer	Targeted Devices	Dynamics of routing	Routing IP	Routing Optical	Physical layer constraints	Constraints on installed devices	Impact on QoS	Computation time	Triggering events	Operation	Network knowl.	Protection consid.	Reconfiguration cost	Future traffic assumption	Control mechanisms
Routers targeted for power saving																
GDRP-PS [212], Ho 2010	n/c	Routers	IP	SPR, ShPR	n/c	n/c	included (all devices)	overprov.	n/r	exceeding util. thresholds	distr.	global	no	n/c	unknown	ad hoc
LNF/LLN [176, 219], Kist & Aldraho 2010	n/c	Routers	IP	SPR	n/c	n/c	included (IP routers)	overprov.	n/r	n/r	centr.	global	no	n/c	unknown	n/c
G-Game [220], Bianzino 2011	n/c	Routers	IP	MPR	n/c	n/c	included (all devices)	Shapley value	n/r	n/r	centr.	global	no	n/c	known	n/c
RSTA[18] [221], Cianfrani 2012	n/c	Routers	IP	SPR, ShPR, Floyd-Warshall	n/c	n/c	included (IP links)	min. load in Demand Reassignment	n/r	n/r	centr.	global	no	n/c	known	n/c
Routers and Other Devices targeted for power saving																
LFA, MPA, Random [179, 180, 195, 222, 223], Chiaraviglio 2009[19]	n/c	Routers, LCs, TSPs (IP links) [20]	IP	SPR, ShPR	n/c	n/c	included (all devices)	overprov.	secs.	TM change	centr.	global	no	n/c	known	n/c
LNH_solve [157], Niewiadomska-Szynkiewicz 2013	SDH	Routers, LCs, ports	IP	SPR	n/c	n/c	included (all devices)	n/c	0.161-29.499 s	n/r	centr.	global	no	n/c	unknown	ECONET framework [213, 214]
MILP, H-GreenRE[21] [165–167, 224][22], Giroire, Coudert 2012	n/c	Routers, LCs	IP	SPR	n/c	n/c	included (all devices)	overprov.	2 hours (MILP)	TM change	centr.	global	no	n/c	known	n/c
E2-MCRA [215], Avallone 2012	n/c	Routers, LCs	IP	SPR	n/c	n/c	included (LCs)	blocking rate, throughput, overprov.	n/r	flow request	centr.	global	no	n/c	unknown	MPLS
RPP-SP, RPP-T [225], Mumey 2012	n/c	Routers, LCs	IP	SPR	n/c	n/c	included (all devices)	overprov.	n/r	TM change	centr.	global	no	n/c	known	n/c
PAFRP, PAVRP, EA-STH, EA-LG [162–164], Addis 2012	n/c	Routers, LCs	IP	SPR	n/c	n/c	included (all devices)	overprov.	5 min (PAVRP online), 6 hours (PAVRP offline), 32-153 s (EA-LG)	TM change	centr.	global	no	number of reconfigurations	known	n/c
TLPH and PMH [178], Garroppo 2012[23]	n/c	Routers, LCs	IP	MPR	n/r	n/c	included (nodes and links)	overprov.	mins	TM change	centr.	global	no	n/c	known	n/c
MILP-EWO [169, 170], Amaldi, Capone, 2013	n/c	Routers, LCs	IP	SPR	n/c	n/c	included (all devices)	overprov.	59-4863 s	TM change	centr.	global	no	n/c	known	n/c
MILP-MMF, RPH [210], Amaldi 2013	n/c	Routers, LCs	IP	SPR	n/c	n/c	included (all devices)	overprov.	seconds-hours	TM change	centr.	global	no	n/c	known	n/c

Continued on next page

[18]Three versions of the RSTA are considered in [221], where different sorting criteria (degree-based, betweenness-based, and traffic-based) are used for the initial list of nodes provided to the Floyd-Warshall algorithm.

[19]Note that the only difference between LFA, MPA, Random is the policy for sorting nodes and links [180].

[20]Power consumption of REGs is taken into account in [180, 222]

[21]RE routers are assumed

[22][166] includes robust constraints

[23]A MINLP formulation and two different heuristics are proposed in [178].

TABLE VI Energy-Aware Network Operation (EA-NO) approaches targeting power saving in IP layer – continued from previous page.

Method's Name, First author(s), Year of the first publication	Optical layer	Targeted Devices	Dynamics of routing	Routing IP	Routing Optical	Physical layer constraints	Constraints on installed devices	Impact on QoS	Computation time	Triggering events	Operation	Network knowl.	Protection consid.	Reconfiguration cost	Future traffic assumption	Control mechanisms
AGA, GLGA [174], Wang 2014	n/c	Routers, LCs	IP	SPR	n/c	n/c	included (all devices)	overprov., delay	n/r	TM change	centr.	global	no	n/c	known	n/c
MILP, STPH, STPH-RP [175], Addis 2014	n/c	Routers, LCs	IP	SPR	n/c	n/c	included (all devices)	overprov.	30-1200 s (STPH, STPH-RP)	timer	centr.	global	SPP, DPP	considered (power switching state)	known	n/c
MILP [181], Bianzino 2010	n/c	Routers, IP links	IP	MPR	n/c	n/c	included (nodes and links)	overprov.	n/r	TM change	centr.	global	n/c	n/c	known	n/c
EET [209], Lai 2011	n/c	Routers, IP links	IP	SPR	n/c	n/c	included (all devices)	overprov., max. link utilization variation	n/r	TM change	centr.	global	no	n/c	known	n/c
GAPS [173], Cheung 2014	n/c	Routers, IP links	IP	SPR	n/c	n/c	included (all devices)	overprov.	n/r	TM change	centr.	global	no	n/c	known	n/c
ILP with DLP [177], Aldraho 2012	n/c	Routers, IP links	IP	MPR	n/c	n/c	included (all devices)	overprov.	n/r	TM change	centr.	global	DLP	n/c	known	n/c
ILP with DPP [177], Aldraho 2012	n/c	Routers, IP links	IP	MPR	n/c	n/c	included (all devices)	overprov.	n/r	TM change	centr.	global	DPP	n/c	known	n/c
LCs and Other Devices targeted for power saving																
VLCM [226–228], Bolla 2010	WDM	LCs, TSPs (IP links)	no[24]	SPR, ShPR	n/c	n/c	included (routers and LCs)	IP transparency	secs.	change of IP traffic demand	centr.	global	no	n/c	known	n/c
FUFL [193, 194, 217, 218], Idzikowski 2010[25]	WDM, any	LCs, TSPs (lightpaths)	no	like in SBN	like in SBN	consid. (all constraints)	included (all devices)	overprov.	subsecs.	exceeding util. thresholds	distr.	local	no	no reconfiguration	unknown	not needed
DAISIES [128, 233, 234], Coiro 2011	WDM	LCs, TSPs (lightpaths)	IP[26]	SPR, ShPR, Dijkstra	n/c[27]	n/c[28]	included (routers and LCs)	overprov.	subsecs.	change of IP traffic demand	distr.	global	no	n/c	unknown	MPLS rerouting
L-Game [235], Bianzino 2012	n/c	LCs, TSPs (IP links)	IP	MPR, ShPR	n/c	n/c	included (all devices)	Shapley value	secs.	TM change	centr.	global	no	n/c	known	n/c
GA [195, 223], Bonetto 2013	WDM	LCs, TSPs (lightpaths)	IP	SPR, ShPR	n/c	n/c	included (LCs and routers)	overprov.	mins.	TM change	centr.	global	no	rerouted traffic	known	n/c
EWA [195, 236, 237], Idzikowski 2013	WDM	LCs, TSPs (lightpaths)	IP	SPR, ShPR, BFS	n/c	n/c	included (routers and LCs)	overprov.	subsecs.-secs.	exceeding util. thresholds	centr.	global	no	prev. network config. usage	unknown [237], known [195]	n/c
BA [238, 239], Yamanaka & Takeshita 2010	n/c	LCs, switching fabrics	IP	SPR, ShPR, Dijkstra	n/c	n/c	included (IP links)	overprov. & max. IP hops	subsecs.-secs.	n/r	centr.	global	Disjoint Multi-route divergence	n/c	known	GMPLS extension
OH/CS, OH/AS, MH/SOH, MH/ST [216], Scharf 2012	n/c	LCs and IP traffic processing (lightpaths)	IP (with LT changes)	n/r	n/c	full wavelength conver.	n/c	n/c	n/r	exceeding transit traffic thresholds	distr. (OH/CS, OH/AS), centr. (other)	local	no	n/c[29]	unknown	make-before-break

Continued on next page

[24] Rerouting takes place in an intermediate layer between IP and WDM layers in [226–228].
[25] A similar concept to FUFL (extended to different types of networks) is used in [229–232].
[26] Possibility of changing the LT is considered in [233], but realization of the links (including routing of lightapths) is not considered.
[27] Load Based Cost (LBC) was applied to the Distributed and Adaptive Interface Switch off for Internet Energy Saving (DAISIES) solution in [128].
[28] Least Cost Wavelength (LCW) was applied to the DAISIES solution in [128].
[29] Mean number of bypass establishments is analyzed in [216].

TABLE VI Energy-Aware Network Operation (EA-NO) approaches targeting power saving in IP layer – continued from previous page.

Method's Name, First author(s), Year of the first publication	Optical layer	Targeted Devices	Dynamics of routing	Routing IP	Routing Optical	Physical layer constraints	Constraints on installed devices	Impact on QoS	Computation time	Triggering events	Operation	Network knowl.	Protection consid.	Reconfiguration cost	Future traffic assumption	Control mechanisms
ESA-STH (MILP) [171, 172], Addis 2012	n/c	LCs, chassis, TSPs (lightpaths)	IP	SPR	n/c	n/c	included (routers and LCs, all)	overprov.	limits: 1 min ESA-STH, 2 hours MILP	TM change	centr.	global	IP, shared	on/off limit	known	MPLS
SAA [240], Feller 2012	n/c	LCs, TSPs and electr. traffic switching (lightpaths)	LT changes with deterministic IP routing	SPR, ShPR (geographically)	n/c	n/c	n/c	basic LT	~0.5-175 s [30]	timer	centr.	global	no	reconfig. penalty, prev. network config. usage	known	make-before-break
SAAPP, GEH, MILP [196], Feller 2013	n/c	LCs, TSPs and electr. traffic switching (lightpaths)	LT changes with deterministic IP routing	MPR	n/c	n/c	n/c	basic LT	4-8 min, limit of 1 min for MILP	timer	centr.	global	no	reconfig. penalty, prev. network config. usage	known	make-before-break
VTCR [241], Feller 2013	WDM	LCs, TSPs and electr. traffic switching (lightpaths)	LT changes with deterministic IP routing	MPR, preferably ShPR (geographically)	SPR	max. lightpath length, channel allocation	included	blocking penalty	2-4 min	timer	centr.	global	no	reconfig. penalty	known	one-step reconfiguration
GreenTE MILP [161], Zhang 2010	n/c	LCs with ports	IP	SPR or MPR[31]	n/c	n/c	included (LCs)	n/c[32]	65 s - 28 h[33]	timer (5, 15 min)	centr.	global	no	n/c	known	MPLS extension
LCs targeted for power saving																
MILP, LLEH, RH [197–199], Giroire 2010	n/c	LCs	IP	SPR, MPR	n/c	n/c	included (LCs)	overprov.	n/r	TM change	centr.	global	no	n/c	known	n/c
ESACON [242], Cuomo 2011	n/c	LCs	IP	SPR, ShPR, Dijkstra	n/c	n/c	included (IP links)	algebraic connectivity threshold γ_{th}	n/r[34]	n/r	distr./ centr.	global	no	n/c	unknown	OSPF control messages
ESOL[35] [243], Cuomo 2011	n/c	LCs	IP	SPR, ShPR, Dijkstra	n/c	n/c	included (IP links)	n/c	n/r[36]	n/r	distr.	global	no	n/c	known	n/c
LAP [244], Souda 2012	n/c	LCs	IP	SPR	n/c	n/c	included (LCs)	overprov.	n/r	traffic increase	centr.	global	no	n/c	unknown	n/c
Switch-On (with & without hidden bypass) & Switch-Off MILPs [158–160], Caria 2011	WDM	LCs	IP with changes of LT	SPR	precomputed	n/c	max. number of ports[37]	overprov.	n/r	exceeding util. thresholds	centr.	global	basic IP topology connectivity (Switch-On)	routing penalty	known	n/c
ES-ROD [208], Shen 2012	n/c	LCs	IP	MPR	n/c	n/c	included (LCs)	overprov.	n/r	TM change	centr.	global	no	n/c	known	n/c

Continued on next page

[30]Computation times are provided for the Atlanta network with 15 nodes and 22 bidirectional links in [240].
[31]One of KShP in the simplified MILP [161].
[32]Routing stability is analyzed in [161].
[33]Computation times are provided for the AT&T network with 115 nodes and 296 links in [161].
[34]Complexity of $\mathcal{O}(E \cdot N^2)$ is reported in [242], where E is the number of bidirectional IP links, and N is the number of routers in the network.
[35]Four versions of the Energy Saving based on Occurrence of Links (ESOL) algorithm are proposed in [243], i.e., basic-ESOL, fast-ESOL, $(f+b)$-ESOL and $(f \times 2)$-ESOL.
[36]Complexity of $\mathcal{O}(Niter \cdot N^2 log_2 N)$ is reported in [243], where $Niter$ is the number of iterations, and N is the number of routers in the network.
[37]No capacity constraints for the transport network are considered in [158–160].

TABLE VI Energy-Aware Network Operation (EA-NO) approaches targeting power saving in IP layer – continued from previous page.

Method's Name, First author(s), Year of the first publication	Optical layer	Targeted Devices	Dynamics of routing	Routing IP	Routing Optical	Physical layer constraints	Constraints on installed devices	Impact on QoS	Computation time	Triggering events	Operation	Network knowl.	Protection consid.	Reconfiguration cost	Future traffic assumption	Control mechanisms
GVN [204], Ghazisaeedi 2012	n/c	LCs	IP	n/r	n/c	n/c	included (LCs)	overprov.	n/r	TM change	centr.	global	no	n/c	known	virtual networks
Port grouping MILP and a heuristic OPG [190], Lui 2012	n/c	LCs	IP	SPR	n/c	n/c	included (LCs)	n/c	n/r	n/r	centr. (MILP), dist. (heuristic)	global (MILP), local (heuristic)	no	n/c	known	n/c
GRiDA [245, 246], Bianzino 2011	n/c	LCs [38]	IP	SPR, ShPR, BFS	n/c	n/c	included	overprov.	n/r[39]	LSA arrival	distr.	global (LSAs)	no	n/c[40]	unknown	signal. with LSAs of OSPF or ISIS
EAR[41] [247–249], Cianfrani 2011	n/c	LCs	IP	SPR, ShPR, Dijkstra	n/c	n/c	included (IP links)	overprov.	n/r[42]	exceeding util. thresholds	distr.	global	no	traffic variation on a link due to exportation	unknown	LSAs of the OSPF
DLF & DMP [189], Bianzino 2012	n/c	LCs [43]	IP	SPR, ShPR	n/c	n/c	included (all devices)	overprov., connect. check	n/r	every 10-20 s	distr.	local	no	n/c[40]	unknown	periodic LSAs
ESTOP [250], Cuomo 2012	n/c	LCs	IP	SPR, ShPR, Dijkstra	n/c	n/c	included (IP links)	n/c[44]	n/r[45]	n/r	distr.	global	no	n/c	unknown	LSAs of the OSPF, make-before-break
DGB, DGA [251], Yang 2013	n/c	LCs	IP	SPR	n/c	n/c	included (LCs)	overprov., path stretch	n/r	operator's decision or TM change	distr.	global	no	n/c	unknown	n/c
B-EMP, B-E2SIR [186, 252], Chiaraviglio 2012	n/c	LCs	IP	SPR	n/c	n/c	included (LCs)	overprov.	secs.	TM change	centr.	global	no	number of reconfigurations	known	n/c
TLS, TLS-SLFP [202], Francois 2013	n/c	LCs	IP	SPR	n/c	n/c	included (LCs)	overprov.	n/r	TM change	centr.	global	single link failures (TLS-SLFP)	n/c	known	MPLS
GLA [184, 185], Francois 2013	n/c	LCs	IP	SPR	n/c	n/c	included (LCs)	overprov., max. propagation delay [185]	n/r	TM change	centr.	global	no	n/c	known	n/c
TLB[46] [191, 192], Coiro 2013	n/c	LCs (off or TLB state)	IP	SPR	n/c	n/c	included (IP links)	overprov.[47]	n/r[48]	n/r	centr.	global	TLB state	n/c	known	n/c

Continued on next page

[38]Power consumption of REGs is also taken into account in [245, 246].

[39]The time complexity of the GReen Distributed Algorithm (GRiDA) scales linearly with number of nodes and exponentially with node degree [246].

[40]Number of OFF⇒ON and ON⇒OFF events is analyzed in [189, 245, 246].

[41]The term Energy Saving IP Routing (ESIR) instead of Energy-Aware Routing (EAR) used in [249]. Max_Compatibility and QoS-aware_Max_Compatibility heuristics considered in [248, 249] and [249], resp.

[42]No increase of complexity with respect to Open Shortest Path First (OSPF) is reported in [247].

[43]Power consumption of REGs is also taken into account.

[44]Increase of path length in terms of IP hops, mean utilization of the links, and fairness of traffic distribution on all links are analyzed in postprocessing in [250].

[45]Complexity of $\mathcal{O}(M \cdot N^2)$ is reported in [250], where M is the number of iterations, and N is the number of routers in the network.

[46]A MILP formulation [191, 192] and a heuristic based on a genetic algorithm [191] are proposed. Both use the Table Lookup Bypass (TLB).

[47]The average path length in terms of IP hops is analyzed in postprocessing in [192].

[48]Complexity of $\mathcal{O}(|\nu|^5)$ is reported in [192], where $|\nu|$ is the number of nodes in the network.

TABLE VI Energy-Aware Network Operation (EA-NO) approaches targeting power saving in IP layer – continued from previous page.

Method's Name, First author(s), Year of the first publication	Optical layer	Targeted Devices	Dynamics of routing	Routing IP	Routing Optical	Physical layer constraints	Constraints on installed devices	Impact on QoS	Computa-tion time	Triggering events	Operation	Network knowl.	Protection consid.	Reconfi-guration cost	Future traffic assumption	Control mecha-nisms
EAR-SDN-MILP, EAR-SDN-H [200, 201], Giroire 2014	n/c	LCs	IP	SPR	n/c	n/c	included (LCs)	overprov.	66-150 min EAR-SDN-MILP, 1-10 s EAR-SDN-H	TM change	centr.	global	no	n/c	known	Open Flow
MILP [156], Jaskóła 2014	n/c	LCs	IP	SPR	n/c	n/c	included (all devices)	overprov.	n/r	TM change	centr.	global	no	n/c	known	policy-based routing
GPE [253], Chiaraviglio 2015	n/c	LCs	IP	SPR, ShPR, Dijkstra	n/c	n/c	included (IP links)	overprov.	n/r	TM change	centr.	global	no	traffic variation on a link due to a partial exportation	un-known	LSAs of the OSPF
Other Devices targeted for power saving																
DSA [254, 255], Yonezu 2010	n/c	IP links	IP	SPR, ShPR, Dijkstra	n/c	n/c	included (IP links)	overprov.	subsecs.-mins.	n/r	centr.	global	no	n/c	known	n/c
DELM, MILP [205], Lee 2011	n/c	IP links	IP	SPR	n/c	n/c	included (links)	overprov.	n/r	TM change (MILP), exceeding util. thresholds (DELM)	centr. (MILP), distr. (DELM)	global	no	n/c	known (MILP), un-known (DELM)	n/c
MILP [206], Lee 2012	n/c	IP links	IP	SPR	n/c	n/c	included (links)	overprov.	n/r	TM change	centr.	global	SLP	n/c	known	n/c
LR, HS and LR&HS [188], Lee 2012	n/c	IP links	IP	SPR, ShPR	n/c	n/c	included (all devices)	overprov.	n/r	TM change	centr.	global	no	n/c	known	n/c
GBDA [256], Song 2014	n/c	IP links	IP	KShP	n/c	n/c	included (IP links)	overprov.	n/r	operator's decision or TM change	distr.	global	no	n/c	un-known	MPLS rerouting
LTL, LDB, LDM (switch off heuristics), RL, RB, RM (switch on heuristics) [257], Kamola 2014	n/c	IP links	IP	SPR	n/c	n/c	included (IP links)	overprov.	n/r	total traffic increase / total traffic decrease	centr.	global	no	n/c	known	n/c
GreenFRR [258], Yang 2014	n/c	IP links	IP	SPR	n/c	n/c	included	overprov.	n/r	n/r	centr.	global	no	n/c	known	LSAs of the OSPF
DEER [187], Zhou 2014	n/c	IP links	IP	MPR	n/c	n/c	included (all devices)	overprov.	n/r	exceeding transit traffic thresholds	distr.	local	no	n/c	un-known	periodic LSAs
A-ESR [182, 259], Kim 2011	n/c	links	IP	n/r	n/c	n/c	n/c	factor trading energy and delay	1.14 s for NSFNET (1)	flow arrival	distr.	local	natural	n/c	un-known	artificial ants
ATD [260], Charalambides, Tuncer 2103	n/c	bundled links	IP	MPR	n/c	n/c	included (LCs)	overprov.	n/r	operator's decision	distr.	global	no	n/c	known	edge nodes
GBP [183], Francois 2014	n/c	bundled links	IP	SPR	n/c	n/c	included (LCs)	overprov.	n/r	operator's decision	distr.	global	single link failures	n/c	un-known	MPLS
MILP, R-GR [207], Lin 2015	n/c	bundled links	IP	KShP	n/c	n/c	included (links)	overprov., TR, RR	n/r	TM change	centr.	global	SLP	n/c	known	n/c

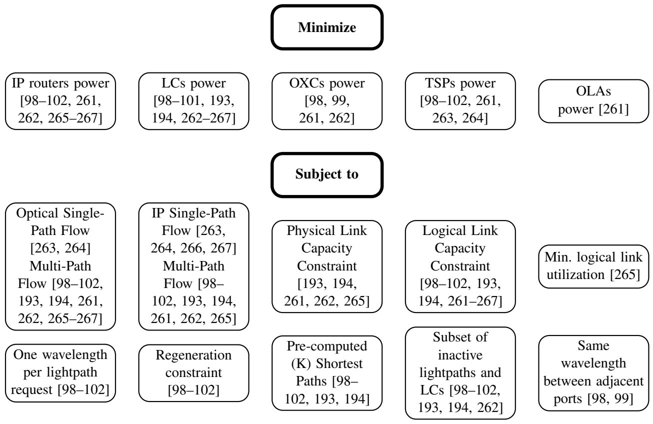


Fig. 8. MILP formulation for the Energy-Aware Network Operation (EA-NO) – IP and optical layers.

Focusing then on operation, it can be either centralized or distributed in the network (e.g., each node manages the set of its incident links). Moreover, the network knowledge is in general global. This is also a reasonable assumption since changing the link power state may lead to a change in the routing in the network, thus potentially affecting other links in the topology. Additionally, protection and reconfiguration costs are rarely considered. We therefore expect that future work will integrate both these aspects. Finally, different works assume future traffic to be known, and exploit standard control mechanisms (like LSAs of the OSPF, MPLS, and Open Flow).

Other Devices: This category includes approaches targeting either generic IP links or generic bundled links. Since generic devices are adopted (without going into technological detail), only IP routing is considered, without exploiting the optical layer and its routing capabilities. Different IP routing strategies can be adopted such as the ones using single or multiple paths, and single shortest path or KShP. Clearly, shortest paths or KShP are two valid alternatives to ensure a limited number of traversed hops. The physical layer constraints are not considered at all (as expected), while the constraints on the installed devices are generally included. Moreover, the impact on QoS is usually controlled by the classical overprovisioning. Alternatives to the overprovisioning are envisioned for future works. Unfortunately, computation time is not reported (except for two approaches). Again, we stress the importance of assessing the time required to obtain a solution, in order to make an EA-NO algorithm ready for its practical implementation. Focusing on the remaining categories, we can see that considerations similar to the LC category hold. While several control mechanisms are used by the surveyed approaches, we expect future approaches to: (1) ensure protection, (2) consider reconfiguration costs, and (3) assume future (unknown) traffic.

D. IP and optical layers

We first detail the formulation in Section IV-D1. We then present the comparison of the surveyed approaches in Section IV-D2.

1) Formulation: Fig. 8 reports the problem formulation. The objective function targets the minimization of power consumption at both layers. In particular, power consumption minimization of LCs and IP routers is targeted at the IP layer. Moreover, power consumption reduction of OXCs, TSPs and OLAs is considered at the optical layer.

Focusing then on the constraints, routing (either via single paths or multiple paths) is considered at both layers. Moreover, link utilization should not exceed the link capacity (at both layers). Eventually, a minimum logical link utilization can be introduced, i.e., lightpaths whose utilization is below a given threshold should be deactivated in order to increase the energy-saving. Additionally, a single wavelength should be allocated for each lightpath request. Moreover, the number of active REGs at each node should be bounded by the number of incoming paths. Finally, the set of paths can be pre-computed, so that the approach can take one or more out of K-pre-computed paths between each node pair.

As an alternative version, the problem can be formulated in an incremental way considering time-varying demands. In particular, the MILP is solved several times, assuming that traffic is decreasing between one run and the following one. In this case, the subset of deactivated lightpaths and LCs by the current MILP has to include the devices deactivated after the execution of the previous MILP. This constraint is inserted in order to limit the number of device reconfigurations and the amount of traffic which has to be rerouted in the network. Finally, the same wavelength should be used between adjacent ports.

2) Comparison of Approaches: Table VII reports the main characteristics of the surveyed EA-NO approaches targeting energy saving in IP and optical layers. In particular, the approaches reported in Table VII are ordered according to the following categories of targeted devices: (1) routers and other devices, and (2) LCs and other devices. The limited number of works highlights that the research on operation of IP and optical layers is at an early stage of development.

Routers and Other Devices: In this category all approaches targeting routers together with OXCs, TSPs, REGs, OLAs, MUXs/DEMUXs, and WLCTs are considered. The first outcome of Table VII is that only approaches assuming WDM in the optical layer are proposed. Accordingly, further work is required to provide new approaches for EONs. Dynamics of routing is assumed in both layers in all the surveyed approaches. Optical layer and IP layer routing are mainly based on MPR, obtained solving a MILP formulation. The main consequence of this feature is that the computation times are high (i.e., hours). This aspect represents a considerable limitation to apply the proposed approaches in operational networks.

Even in this case, wavelength assignment is the most widely considered physical constraint. The constraints on installed devices are also taken into account. There is no agreement on a method to limit the impact on QoS: the blocking probability, overprovisioning and differentiated traffic are used. Triggering events correspond to traffic variation and scheduled events (including timer expiration).

All the reported approaches are centralized with global network knowledge. This is an expected outcome, considering the complexity of jointly solving the IP and optical layer routing. Astonishingly, protection and reconfiguration costs are not considered apart from the top-down scheme used in [262]. Both aspects are a mandatory goal for an approach covering different layers. The assumption to know future behavior of traffic is made by most works while control mechanism have not yet been deeply investigated in this category.

LCs and Other Devices: The approaches targeting LCs together with TSPs, OXCs, and OLAs are reported here. The main difference with respect to the case of router-related approaches regards the IP and optical routing. All the reported approaches are based on SPR obtained from the heuristic EA-NO approaches. In this way the complexity is lower with respect to the previous category allowing for easier implementation in real networks. This evaluation is strengthened by the reported computation times and by the availability of a distributed approach (DAISIES + Power-Aware Routing and Wavelength Assignment (PA-RWA) [128]).

TABLE VII: Energy-Aware Network Operation (EA-NO) approaches targeting power saving in IP and optical layers.

Method's Name, First author(s), Year of the first publication	Optical layer	Targeted Devices	Dynamics of routing	Routing IP	Routing Optical	Physical layer constraints	Constraints on installed devices	Impact on QoS	Computation time	Triggering events	Operation	Network knowl.	Protection consid.	Reconfiguration cost	Future traffic assumption	Control mechanisms
Routers and Other Devices targeted for power saving																
Auxiliary Graph heuristics RSB and LUB, RDB and TDB [268–270], Hasan & Farahmand 2010	WDM	IP routers, ports	IP and optical	SPR in Auxiliary Graph	SPR in Auxiliary Graph	consid. (WA)	included (all devices)	differentiated traffic	n/r	timer	centr.	global	no	n/c	known	n/c
Three MILP formulations [262, 265], Zhang 2010	WDM	IP routers, LCs (& OXCs in [262])	IP and optical	MPR	MPR	consid.	included[49]	n/c	hours	TM change	centr.	global	no	top-down scheme	known	n/c
MILP with Connectivity Graph [98–101], Rizzelli & Morea 2012	WDM	IP routers[50], LCs, TSPs, OXCs, REGs	IP and optical	MPR	MPR	consid. (WA, lightpath length)	included (all devices)	no[51]	hours	total traffic increase by 5%	centr.	global	no	n/c	known	n/c
MILP PIRTS PIR [261], Wu 2014	WDM	IP routers, TSPs, OXCs, OLAs,	IP and optical	MPR	MPR	consid.	included (all devices)	blocking probability	n/r	flow arrival	centr.	global	no	n/c	known	n/c
P-MIN P-PRO E-MIN, E-PRO [271], Schoendienst 2014	WDM	IP routers, TSPs, OXCs, OLAs, MUXs, DEMUXs, WLCTs	IP and optical	SPR	SPR	consid. (WA)	included (all devices)	overprov.	n/r	flow arrival	centr.	global	no	n/c	known	n/c
MILP with Connectivity Graph [102], Rizzelli 2013	WDM	IP routers, TSPs, REGs	IP and optical	MPR	MPR	consid. (WA, lightpath length)	included (TSPs and REGs)	n/c	hours	total traffic increase by 5%	centr.	global	no	n/c	known	Cited [272] – GMPLS extension
MILP and simulation with TATG [266, 267], Zhang 2011	WDM	IP routers, LCs, WLCTs	IP and optical	SPR, Dijkstra for TATG	MPR	WA	n/c	n/c [52]	hours (MILP), n/r (TATG)	arrival/termination of traffic demand	centr.	global	no	n/c	unknown	n/c
LCs and Other Devices targeted for power saving																
EAAG [273], Yang, Kuipers 2011	WDM	LCs, TSPs, OXCs	IP and optical	SPR	SPR, specific link weights	WA, wavelength conversion	n/c	wavelength usage	complexity analysis	flow arrival	centr.	global	no	n/c	unknown	n/c
ILPFSD, ILPSSD, HEER [263, 264], Chen 2011	WDM	LCs, TSPs	IP and optical	SPR	SPR	n/r	included (all devices)	overprov.	n/r	scheduled event	centr.	global	no	n/c	known	n/c
Two steps: DAISIES + PA-RWA (LBC and LCW) [128], Coiro 2012	WDM	LCs, OXCs, OLAs	IP and optical	ShPR[53]	ShPR[54]	consid. (WA)	included (all devices)	n/c	subsecs.	change of IP traffic demand	distr.	global	no	n/c	known	n/c
TDGTG [274], Zhang 2014	WDM	LCs, TSPs, OXCs, OLAs	IP and optical	SPR	SPR	consid. (WA)	included (all devices)	overprov.	n/r	scheduled event	centr.	global	no	n/c	known	n/c

[49] The mathematical formulation in [262] ensures the constraint on the installed fibers, but only partly addresses the constraint on the installed chassis, LCs and OXCs.
[50] Slave shelves, slave racks, router chassis are distinguished in [98–101].
[51] Maximum utilization of resources is analyzed in [98].
[52] Avg. number of hops and blocking probability are analyzed in [267].
[53] Time variant link weights at the IP layer are used in [128].
[54] LBC with time variant link weights at the WDM layer are used in [128].

V. Network scenarios

We consider the network scenarios that are used in the literature, differentiating between: (1) traffic, (2) network topologies, and (3) power consumption models.

A. Traffic

Traffic is an essential parameter for both network design and operation. For network design, it determines the amount and type of energy-consuming devices that need to be deployed, so it will significantly affect the total energy consumption. Regarding network operation, the majority of the EA approaches exploit the temporal traffic variations to achieve energy savings. Therefore, the assumed traffic behavior (e.g., diurnal vs. night traffic) will be a key parameter when evaluating any EA approach.

The traffic patterns found in the literature can be classified into model-based (Table VIII(a)) and measurement-based (Table VIII(b)). Model-based traffic is commonly used when accurate real traffic information is unavailable or when controlled variation of traffic is necessary. On the other hand, the measurement-based traffic reflects real traffic measurements or projections provided by network operators. The measurements can also be used to parametrize the traffic models in order to make the model-based traffic as realistic as possible. Furthermore, we distinguish between spatial and temporal distributions. The former determines the aggregated traffic demands between node pairs, i.e., the TM, whereas the latter determines changes of TMs over time.

Model-based traffic: Random traffic generation is the most common way to determine spatial traffic distribution as shown in Table VIII(a). The uniform distribution has been widely used in the literature to artificially model the traffic, however non-uniform distributions are also used in several of the surveyed works. Some publications do not explicitly mention what kind of random distribution is employed. The uniform distribution does not prioritize any nodes regarding generated or received traffic. This is however usually not the case in real networks. Hence the gravity and population-based models are used (in 10 and 12 papers, respectively). Another approach to spatial traffic generation is a synthetic model, where traffic demands between each node pair consist of a few high- and low-rate components.

For the temporal traffic distributions, the sine-like functions are often used to model traffic variation in the IP layer, while in the optical layer, the Poisson and exponential distributions are frequently employed to model the arrival time and holding time of the lightpaths, respectively. Other works emulate the dynamic traffic behavior considering Auto Regressive Integrated Moving Average (ARIMA) (a time series analysis method to characterize diurnal traffic variation), peak and off-peak traffic, some unspecified random distribution or deterministic traffic.

Measurement-based traffic: Measuring traffic in backbone networks is not trivial. This is particularly the case when traffic demands between all node pairs are required (spatial traffic distribution). Table VIII(b) presents a summary of the traffic distributions based on measurements used in the surveyed literature. For the spatial distributions, real measurements and traffic projections for well-known network topologies can be distinguished. The access to real measurements is limited to a set of TMs provided by the network operators. As can be noticed, most of the TMs are stored in the publicly available SNDlib library [293]. Some of the TMs were provided within the context of publicly funded projects such as the EU-funded project DICONET or TREND [124, 276]. The majority of the TMs was published some years ago and might be outdated. A common approach to emulate the current or future traffic is to scale up the reference TMs (dated some years ago) [51, 60]. Nevertheless, it is worth mentioning that traffic could have significantly changed over time and might not have grown at the same pace in all the parts of the network. Several traffic projections are used in the surveyed works. The projections represent an intermediate approach between the traffic measurements and traffic models. Traffic volumes in the projections correspond to the state-of-the-art network technologies (such as WDM and EON), but they cannot forecast future traffic behavior with no mistake.

Concerning the traffic variations over time, some information can also be found for different network topologies in [293], but most of the time-varying TMs were collected long time ago. These TMs are based on real IP traffic measurements, and available with different time granularities (from 5 minutes to 1 month). Moreover, it must be taken into account that traffic increases exponentially over longer time horizons, but it also fluctuates heavily over the day or week. Therefore, it might also be useful to have access to TMs considering different time horizons (e.g., from several days or weeks up to several years) to evaluate the diverse traffic variations in the different weekdays and months. Traffic projections are used also in this case. Eventually, a single traffic profile (relative traffic demand vs. time) is often provided and applied to traffic demand between each node pair.

In conclusion, the access to updated and reliable spatial and temporal traffic information is essential to assess the potential benefits of any EA network operation and design. The choice of model-based traffic or the measurement-based traffic depends on the research question of a particular study. Parameters of traffic models provide the possibility to provide various input data for the experiments (e.g., evaluation of EA-ND and EA-NO approaches) and to perform a sensitivity analysis of the results. On the other hand, the values for the parameters need to be carefully chosen. Therefore traffic measurements are crucial. Out of the reported measurement-based traffic, only the sets of traffic matrices available in the SNDlib library [293] provide spatial traffic distribution for each single time period (time variation). However, shall the research focus be on future networks (in the long term), traffic projections can be considered. We particularly point out the FT projections and TID measurements providing both time variation and (single) spatial distribution. Traffic measurements from single network links (e.g., provided by AMS-IX [297]) are a good choice for evaluation of local energy saving approaches. Measurement-based traffic provides no possibility of generating different load scenarios (no parametrization except for a scaling factor), but captures the unexpected traffic peculiarities that are usually not covered in the model-based traffic. Furthermore, it is usually related to the topology of the network, where the measurements were performed. Overall, our recommendation (in the context of EA-ND and EA-NO) is to use measurement-based traffic. Regarding model-based traffic, we point out the gravity model and population-based models which can be parameterized with measurement values to generate semi-realistic IP traffic. In the optical layer, we point out the Poisson model with exponentially distributed holding time to generate traffic in terms of lightpath requests of certain time duration.

B. Network topologies

The potential energy savings that an EA approach can provide depends on the network topology used for its evaluation (see for example [116]). Table IX and Table X summarize a wide set of network topologies that can be found in the surveyed papers

TABLE VIII
TRAFFIC USED IN THE SURVEYED WORKS.

(a) Model-based traffic

	Type of traffic	Used in
Spatial distribution	Random, uniform distribution	[25, 30, 34, 40, 41, 61–64, 68–70, 72–80, 83, 85, 90–94, 96, 98–102, 106, 107, 109, 110, 118, 120–122, 125–128, 130–133, 136–141, 149, 152, 153, 165, 169, 171–174, 178–180, 189, 190, 192, 204, 209, 215, 216, 233, 234, 239, 244, 254, 255, 261, 264–270, 273–275]
	Random, non-uniform distribution (probability function shown)	[129, 146]
	Random, non-uniform distribution (shown in a table)	[26, 27, 33, 65, 66, 70, 71, 88, 89, 106, 157, 180, 186, 189, 222, 271]
	Random, non-uniform Traffic Matrix (TM) (not shown)	[38, 42, 43, 56, 83, 84, 104, 105, 111–113, 117, 117, 147, 212, 258]
	Random, unknown distribution	[29, 35–37, 97, 103, 115, 117, 177, 182, 188, 221, 259], [240] (deterministic)
	Population-based model	[44, 45, 50–53, 60] (based on [276, 277]), [193, 194] (based on [278]), [86, 87] (based on forecasts [279, 280] and other non-public forecasts), [113] (derived from population correlated measured traffic distribution)
	Gravity model	[7, 161, 191, 207, 208, 256] (based on [281, 282]), [176, 219] (based on [283]), [258] (based on [284]), [98] (based on [285])
	Synthetically generated TM, lognormal distribution [286]	[242, 243, 247–250]
	Synthetically generated TM, Poisson distribution	[169]
	All-to-all TM with equal traffic demands	[116]
Time variation	Sine-like function	[68, 79, 128, 129, 146, 179, 190, 209, 216, 222, 233–235, 244–246, 275, 287, 288]
	ARIMA [289]	[78, 92–96, 118]
	Peak and off-peak	[26, 101, 102, 130–132, 158–160, 173, 212, 249]
	Random variation	[163, 171, 172, 177, 261, 274]
	Poisson arrival with exponentially distributed holding time	[133, 137–139, 149, 152, 153, 266, 267], [182, 259] (tens of thousands of IP flows, rate, holding time and interarrival time exponentially distributed)
	Poisson arrival with negative exponential holding time	[46, 50, 51, 108, 119, 134, 135, 140–143, 145, 147, 154, 155]
	Periodic, deterministic	[27, 136, 162, 164, 175, 176, 186, 188, 219, 222, 240]

(b) Measurement-based traffic

	Type of traffic	Used in
Spatial distribution	Traffic Matrix (TM) from [290, 291]	[158–160, 262]
	Abilene measurements [292, 293]	[81, 82, 161, 166, 170, 183, 194, 195, 197–199, 207, 208, 223, 250, 258, 260]
	Atlanta projections [293]	[165, 168, 171, 172, 197–199]
	COST239 (3) measurements [294]	[28]
	COST266 projections [293]	[165, 197–199]
	France projections [293]	[162–165, 168, 171, 197–199]
	FT projections [124]	[123, 186, 217, 218, 235, 253]
	Géant measurements [293, 295]	[82, 161, 162, 181, 183–185, 187, 194–199, 202, 207, 237, 241, 245, 246, 257, 260]
	Germany17 (DFN) measurements [293, 296]	[81, 82, 165, 172, 175, 193–195, 197–199]
	Germany50 (DFN) measurements [293, 296]	[175, 200, 201, 250, 257]
	Giul39 projections [293]	[165, 197–199]
	New York projections [293]	[163, 165, 197–199]
	Nobel-EU projections [293]	[162–165, 171, 175, 178, 197–199, 210]
	Nobel-US projections [293]	[171, 172]
	Norway projections [293]	[165, 197–199]
	Orange international backbone projections [148]	[148]
	Pioro40 projections [293]	[165, 197–199]
	Polska projecitons [293]	[168, 170–172, 175, 210]
	Telekom Austria measurements [293]	[200, 201]
	Tiger measurements	[220, 235, 245, 246]
	TID measurements [124]	[47–50, 53–55, 57–60, 217, 218]
	Zib54 measurements [293]	[165, 197–201]
Time variation	Abilene measurements [292, 293]	[81, 82, 194, 195, 223, 250]
	Measurement from AMSterdam Internet Exchange (AMS-IX) [297]	[98, 100, 131, 262, 265]
	FT projections [124]	[123, 186, 217, 218, 235, 253]
	Géant measurements [293, 295]	[82, 162, 181, 184, 185, 187, 194–196, 202, 237, 241, 245, 246]
	Germany17 (DFN) measurements [293, 296]	[81, 82, 193–195]
	Germany50 (DFN) measurements [293, 296]	[250]
	Internet2 measurements [298]	[270]
	Italian Network measurements [179]	[179, 180, 186, 189, 245, 246]
	Orange international backbone projections [148]	[131, 148]
	TID measurements [124]	[53, 144, 217, 218]
	Step function taken from measurements	[200, 201]

TABLE IX
NETWORK TOPOLOGIES USED IN THE SURVEYED WORKS (OPTICAL LAYER).

Name	Nodes	Bidir. Links	Mesh degree	Comments
16N23L-network	16	23	0.19	[125] (bidir.)
Abilene [292, 293]	12	15	0.23	[81, 82, 194, 195, 223] (bidir. links)
ARPANet	20	62	0.33	[151] (unidir. links), [264] (links not reported)
Atlanta [293]	15	22	0.21	[216, 240] (bidir. links)
COST239 (1)	11	26	0.47	[28–30, 34, 41, 79, 90, 98, 100, 101, 137, 138, 142, 142] (bidir. links), [83, 89, 104, 106] (bidir. links, single-fiber)
COST239 (2)	11	22	0.40	[35, 36, 130–132] (bidir. links)
COST239 (3)	11	25	0.45	[26] (bidir. links)
DT [276]	14	23	0.25	[44, 45, 51–53, 56, 99, 143] (bidir. links), [97] (12 nodes, 20 bidir. links)
EON	16	23	0.19	[130, 132] (bidir. links), [151] (20 nodes, 78 unidir. links), [61–64] (11 nodes, 26 bidir. links)
Eurocore	11	26	0.47	[117] (bidir. links), [150] (11 nodes, 50 unidir. links), [136] (14 nodes, 20 bidir. links)
Eurolarge	43	90	0.10	[150] (180 unidir. links)
European	26	49	0.15	[65, 66] (undir. links)
European-like	11	16	0.31	[99, 101] (bidir. links), [102] (bidir. single-fiber links)
Géant [293, 295]	22	36	0.16	[82, 194, 195, 237] (bidir. links)
Géant2 [276]	34	52	0.09	[50–52, 143] (bidir. links)
Géant2	22	36	0.16	[147] (bidir. links)
Germany17 (Nobel Germany in [293])	17	26	0.19	[81, 82, 90, 110, 115, 166, 193–195] (bidir. links), [172] (52 unidir. links)
Germany20	20	29	0.15	[86, 87] (bidir. links)
Germany50 [293]	50	88	0.07	[113] (bidir. links)
JPNTT	16	17	0.14	[61, 62] (bidir. links)
NSFNET (1) [291]	14	21	0.23	[26, 31–33, 40, 61–64, 73, 79, 80, 85, 90–96, 104, 118–122, 134, 138, 140–142, 152, 153, 239, 254, 262, 265, 268–271, 274] (bidir. links), [158–160] (bidir. links, 40 unidir. links mentioned in [158], the same topology for the IP layer assumed), [150, 151] (42 unidir. links) [77, 264] (links not reported)
NSFNET14N20L (2)	14	20	0.22	[273] (bidir. links)
NSFNET14N22L (3)	14	22	0.24	[83, 84, 88, 105, 106, 115, 117] (bidir. links)
NSFNET16N23L (4)	16	23	0.19	[37] (bidir. links)
NSFNET24N43L (5)	24	43	0.16	[70, 153, 268–270] (bidir. links)
Pacific Bell	15	20	0.19	[266] (bidir. links)
Orange international backbone	32	42	0.08	[148] (bidir. links)
Pan-European	11	18	0.32	[97] (bidir. links), [133] (27 nodes and 110 unidir. links), [149] (27 nodes, 55 bidir. links), [153] (37 nodes, 57 bidir. links)
Pan-European Transport	25	46	0.15	[128] (bidir. links)
Telecom Italia	31	53	0.11	[65] (bidir. links)
TID [124]	30	96	0.22	[47–50, 53–56, 90, 144, 145] (bidir. links), [57, 58] (150 nodes, 319 bidir. links)
TP	14	24	0.26	[56] (bidir. links)
UKNet	13	11	0.14	[150, 151] (22 unidir. links)
USA66	66	90	0.04	[111, 112] (bidir. links)
USNET13N22L (1)	13	22	0.28	[126, 127] (bidir. links)
USNET24N41L (2)	24	41	0.15	[266, 267] (bidir. links)
USNET24N43L (3)	24	43	0.16	[42, 43, 73, 79, 85, 115, 137, 142, 154, 261, 273, 274] (bidir. links)

for the optical and the IP layers, respectively. For each network topology, we report the number of nodes $|N|$, the number of bidirectional links $|L|$, the mesh degree M, and the references where the particular topology was used. The reported parameters ($|N|$, $|L|$, and M) will affect the number of active devices that have to be deployed in the network, and so the total power consumption. In most of the surveyed works, the basic information regarding the total number of nodes and links is explicitly mentioned in the text or can be obtained from the figures. The network links can be unidirectional (directed) or bidirectional (undirected). We report the number of bidirectional links in the Tables IX and X, and mark deviations in the column "Comments". In general, we treat two unidirectional links as a single bidirectional link, and neglect the difference between directional links and undirected links. Concerning M, it is obtained by the ratio of the average node degree of a particular network topology d, and the node degree d_{mesh} of a full mesh network with same number of nodes ($d_{mesh} = |N| - 1$). Therefore, the mesh degree is defined as $M = 2 \cdot |L|/|N|/(|N| - 1)$ [116, 301], and takes values between 0 and 1.

Tables IX and X contain a diverse set of network topologies ranging from simple graphs with a small number of nodes and links (e.g., Telstra with 7 nodes and 9 links) to more complex ones (e.g., Abovenet [300] with 366 nodes and 968 links or a version of Sprint with 516 nodes and 3186 unidirectional links). It is worth mentioning that different versions of the same topology may appear in the literature, such as the COST239 that is reported with different number of links (i.e., 22, 25 or 26 links). Please note that some synthetic topologies used in some publications are not reported in the tables, since our goal is to gather only information related to realistic network scenarios. Simple topologies (such as the six-node eight-link 6N8L-network topology used in [79, 80, 85, 107, 121, 274]) are removed from the tables, because such topologies are mainly used to demonstrate the concepts of EA approaches, or to verify the formulated MILP problems (impossible to solve for larger topologies). Besides, regular topologies such as Square Grid [198, 199] or Ring [25, 275] are also removed from the tables. Eventually, we note that Random topologies (12-32 nodes) in the optical layer are used in [25, 116, 129, 135, 146, 155], and are not reported in the tables either.

Despite the fact that some topologies found for the IP and the optical layers are the same (e.g., NSFNET (1)), the ones used for

TABLE X
NETWORK TOPOLOGIES USED IN THE SURVEYED WORKS (IP LAYER).

Name	Nodes	Bidir. Links	Mesh degree	Comments
Abilene [292, 293]	12	15	0.23	[166, 168, 250] (bidir. links), [161, 183, 207, 260, 299] (30 unidir. links) [169] (extended topology, 20 nodes, 62 unidir. links), [170] (1 node removed, 11 nodes and 14 bidir. links) [208] (11 nodes and 28 unidir. links)
Abilene	15	22	0.21	[210] (44 unidir. links)
AS 1221 [300]	104	153	0.03	[258] (bidir. links)
AS 1239 [300]	315	972	0.02	[258] (bidir. links)
AS 6461 [300]	138	374	0.04	[258] (bidir. links)
Abovenet 6461 [300]	17	37	0.27	[7] (74 unidir. links) [169] (19 nodes, 68 unidir. links)
Abovenet (1) [300]	22	42	0.18	[178] (bidir. links)
Abovenet (2) [300]	366	968	0.01	[242, 250] (968 bidir. links), [243, 248, 249] (1932 unidir. links)
AT&T [300]	114	148	0.02	[234] (bidir. links), [161, 169] (115 nodes, 296 unidir. links)
Atlanta [293]	15	22	0.06	[165, 168, 197–199] (bidir. links), [171, 172] (44 unidir. links)
CERNET2	25	29	0.10	[174] (bidir. links), [208] (20 nodes and 44 unidir. links)
CESNET	19	30	0.18	[67] (60 unidir. links)
China Telecom	20	44	0.23	[67] (88 unidir. links)
COST239 (3)	11	25	0.45	[205, 244] (bidir. links) [206] (52 unidir. links)
COST266 [293]	37	57	0.09	[165, 197–199] (bidir.)
Ebone 1755 (1) [300]	18	33	0.22	[7] (66 unidir. links)
Ebone 1755 (2) [300]	23	38	0.15	[178] (bidir. links)
Ebone 1755 (3) [300]	87	161	0.04	[169, 182, 258, 259] (322 unidir. links)
Ebone [300]	159	307	0.02	[242, 250] (bidir. links), [226–228, 243, 248, 249] (614 unidir. links), [191] (87 nodes and 161 bidir. links)
EON	19	36	0.21	[206] (72 unidir.)
Exodus 3967 (1) [300]	21	37	0.18	[7, 178] (74 unidir. links)
Exodus 3967 (2) [300]	78	147	0.05	[169, 182, 258, 259] (294 unidir. links)
Exodus [300]	244	540	0.02	[242, 250] (540 bidir. links), [226–228, 243, 247–249] (1080 unidir. links)
France [293]	25	45	0.15	[165, 168, 197–199] (bidir. links), [162–164, 171] (90 sym. unidir. links)
FT [124]	38	72	0.10	[123, 217, 218, 235, 253] (bidir.)
Garr	22	36	0.16	[67] (72 unidir. links)
Géant [293, 295]	22	36	0.16	[90, 120, 181, 196, 204, 241, 245, 246, 257] (bidir. links), [161, 183–185, 187, 202, 207, 260] (23 nodes, 74 unidir. links) [162] (23 nodes, 72 unidir. links) [210] (22 nodes, 73 unidir. links)
Genuity [300]	42	55	0.06	[169] (110 unidir. links)
Germany17 (Nobel Germany in [293])	17	26	0.19	[165, 197–199] (bidir. links) [175] (42 unidir. links)
Germany20	20	98	0.52	[86, 87] (bidir. links)
Germany50 [293]	50	88	0.07	[200, 201, 250, 257] (bidir. links) [175] (176 unidir. links), [113] (with 8 core nodes, 42 metro nodes and 49 bidir. links)
Giul39 [293]	39	86	0.12	[165, 197–199] (bidir. links)
GTE	12	24	0.36	[205] (bidir. links), [206] (50 unidir. links)
Internet2	9	26	0.72	[229–232] (bidir. links), [258] (12 nodes, 15 unidir. links)
Italian Network [222]	373	718	0.01	[180, 186, 189, 222, 245] (bidir. links)
Level3 [300]	63	285	0.15	[191, 234] (bidir. links)
New York [293]	16	49	0.41	[165, 197–199] (bidir. links), [163] (98 unidir. links)
Nobel-EU [293]	28	41	0.11	[162, 165, 178, 197–199] (bidir. links), [163, 164, 171, 175, 210] (82 unidir. links)
Nobel-US	14	21	0.23	[171, 172] (42 unidir. links)
Norway [293]	27	51	0.15	[165, 197–199] (bidir. links)
NSFNET (1)	14	21	0.23	[68, 182, 190, 205, 206, 259] (bidir. links)
NTT	25	56	0.19	[67] (112 unidir. links)
Pioro40 [293]	40	89	0.11	[165, 197–199] (bidir. links)
Polska [293]	12	18	0.27	[168, 170] (bidir. links) [171, 172, 175, 210] (36 unidir. links)
Rediris	18	30	0.20	[67] (60 unidir. links)
Sprint [300]	52	168	0.13	[169, 207] (bidir. links), [178] (43 nodes, 83 bidir. links) [256] (unspecified nodes and links), [248] (516 nodes and 3186 unidir. links), [161] (52 nodes, 296 unidir. links)
Telekom Austria [293]	65	108	0.05	[200, 201, 201] (undir. links), [178] (bidir. links)
Telstra [300]	7	9	0.43	[7] (18 unidir. links)
TID [124]	113	127	0.02	[217, 218] (bidir. links)
Tiger	22	40	0.17	[220, 235, 245] (bidir. links)
Tiscali [300]	41	87	0.11	[191, 234] (bidir. links) [169] (174 unidir. links)
Tiscali 3257 [300]	161	328	0.03	[182, 258, 259] (656 unidir. links)
USANET	24	43	0.16	[119, 120, 122, 190] (bidir. links), [206] (86 unidir. links)
USA28 [300]	28	45	0.12	[169] (90 unidir. links)
Zib54 [293]	54	81	0.06	[200, 201, 201] (bidir. links), [165, 197–199] (80 bidir. links)

the IP layer are commonly denser in terms of number of nodes and links. For instance some IP topologies, such as Abovenet, contain several hundreds of nodes and several thousands of links, which are significantly bigger than the largest optical topology in terms of nodes and links, i.e., the USA66 network which has 66 nodes and 90 links. We also found that there is a larger number of topologies used in the IP layer (55) than in the optical one (37) neglecting the different versions of some topologies. Therefore, the research carried out in the optical layer has to commonly reuse the same network topologies, whereas there is much more variety for the IP layer. For instance, the most widely used network topology for the optical layer, the NSFNET (1) [291], is reported in 49 publications, while the most popular IP topology, the Géant [293, 295], is used in 19 publications.

Concerning the mesh degree M, thanks to its normalization to values between 0 and 1, it is more intuitive than nodal degree in describing the availability of alternative routing paths regardless of the number of nodes. As mentioned above, the mesh degree depends on the number of nodes and links. Commonly, the smaller the network, the bigger the mesh degree. Thus, in the optical layer, the highest mesh degree is 0.47 corresponding to the COST239 (1) and Eurocore networks (11 nodes and 26 links in both cases), whereas the lowest is 0.04 for the USA66 network (66 nodes and 90 links). Similarly, in the IP layer, the Internet2 network (9 nodes and 26 links) presents the highest mesh degree (0.72). On the other hand, the Abovenet (2) (366 nodes and 968 links), and the Italian Network (373 nodes and 718 links) present the lowest mesh degree (0.01).[55] The mesh degree has a clear impact on the energy savings as shown in [301]. For instance, for approaches putting full links into sleep mode, the energy savings could be more remarkable for networks with high mesh degree as it will be easier to concentrate the traffic on a few links while some others could be put into sleep mode. It also influences the resilience of the network as with higher mesh degree, it will be easier to find potential protection paths in the occurrence of failures. Please mind that the mesh degree for ring topologies depends on the number of nodes [301]. The mesh degree of a 3-node ring is equal to 1, it goes down to 0.67 for a 4-node ring, while a 32-node ring has a connectivity degree of only 0.06 [25, 275].

Moreover, the physical size of the network (commonly characterized by the diameter, i.e., the longest shortest path distance between a node pair of the network in km), also has an impact on the total power consumption as it determines the total number of deployed amplifiers, and whether REGs must be deployed. Only few works report this value though (e.g., [56]). Many works report the physical link lengths (e.g., [104]). The network diameter can be estimated based on the geographical size of the region (particularly for the national and continental networks).

We note also that commercial networks (e.g., AT&T, Sprint or DT) as well as research and education networks are used for evaluation of EA approaches. For completeness, we mention synthetic topologies [72, 157, 234] (not shown in Tables IX–X).

In conclusion, we have presented a set of network topologies that could be easily tracked by researchers to evaluate new EA approaches. The evaluation of certain approaches in networks with different conditions (connectivity, size, etc.) is useful to validate their potential benefits.

[55] The networks with the high number of nodes and links usually contain also metro, or even access nodes additionally to the core nodes.

C. Power model

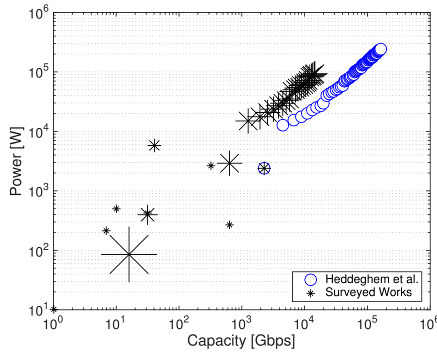
Every study evaluating energy saving in any kind of networks highly depends on the assumption of power consumed by each device in the network. Power models for IP-over-WDM networks based on extensive search of power consumption data originating from product data sheets and measurements reported in research papers can be found in [302, 303]. The authors of [302] propose reference power values for network devices in IP/MPLS, Ethernet, Optical Transport Network (OTN), and WDM layers. They take into account load and environmental conditions (typical power consumption values and not maximum or minimum ones), overhead power consumption (i.e., power consumption due to chassis and network control, excluding external cooling and facilities overhead such as lighting), and bidirectionality of network equipment (i.e., full-duplex). The authors of [303] consider IP and WDM layers, and focus on the Cisco's CRS-3 router, ONS 15454 Multiservice Transport Platform, and Erbium Doped Fiber Amplifier (EDFA) by Finsair. Apart from the static power model, the authors of [303] discuss also dynamic network operation and power scaling, what results in a power model containing static components, dynamic components (devices which are active or inactive), and traffic related components (power scaling with load).

To the best of our knowledge, there is no extensive power model for the EON devices. This is caused by the fact that such devices are still in the development stage, and therefore barely available. Power consumption values of Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) TSPs with different modulation formats can be found in [304].

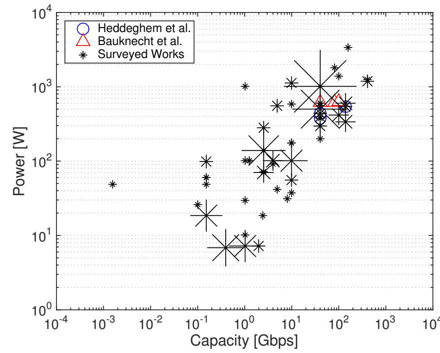
The aim of this survey is different than the ones of [302, 303]. We do not propose a power model based on realistic data from product data sheets, research papers or own measurements, but survey power values that are used as input parameters for evaluation of EA-ND and EA-NO approaches. This provides an insight into how realistic assumptions about power consumption of single devices are made in the surveyed papers, and hence an indication on how realistic the estimated power savings (in absolute numbers) are.

Fig. 9 shows the power consumption values for IP routers, LCs, TSPs, and OLAs found in the surveyed literature. We indicate also the reference power values from [302, 303] in Fig. 9. As presented, the power consumption values vary according to the capacity of the device. Devices of higher capacity commonly consume more power, but they are also more energy-efficient if we consider their power over capacity ratios (W/Gbps). This behavior can be observed for all types of devices except for OLAs (Fig. 9(d)), where power consumption depends on the provided span [302], and not on the capacity (in terms of number of WDM channels).

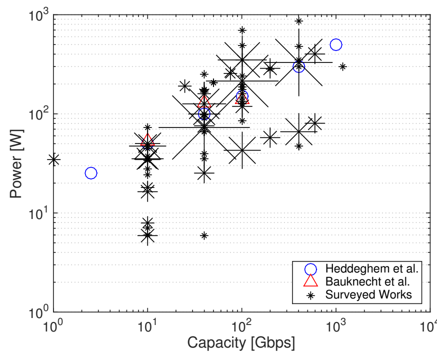
It can be observed from the figures that power consumption assumed for devices working at the same capacity significantly differs (even by several orders of magnitude). There might be multiple reasons for that. First of all, from the limited set of power consumption figures of real products, it is difficult to determine which contributions are included or not (e.g., for OLAs some values account only for the amplifier card, whereas some others may account for the overhead due to controller cards, etc.). Based on these contributions, the power consumption values may vary significantly. Moreover, the energy efficiency of the devices may change over time (average improvements in terms of energy efficiency of 15 per cent per annum are estimated in [305]). Therefore, depending on the year of publication, it may be reasonable to find different power consumption values for the same device. We found no agreement on a single power value for a specific device in a given year. Besides, some of the differences in the values may come from the fact that



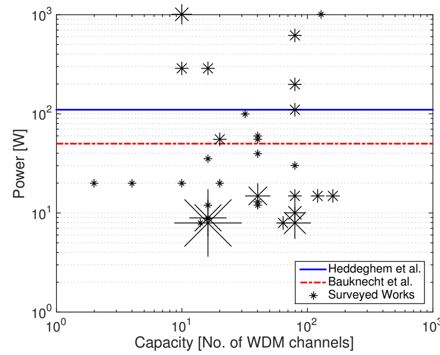
(a) IP Routers, $x \in \{1, 2, 3, 4, 9\}$



(b) LCs, $x \in \{1, 2, 3, 5, 6, 7, 9, 12\}$



(c) TSPs, $x \in \{1, 2, 3, 4, 5, 6, 7, 8, 11, 12, 15\}$



(d) OLAs, $x \in \{1, 2, 3, 4, 5, 6, 11\}$

Fig. 9. Power consumption vs. capacity of IP routers, LCs, TSPs and OLAs. The asterisk marker size is proportional to the number x of surveyed works where the power value from y-axis for a device with capacity from x-axis was used. Reference values from [302, 303] are also plotted.

some vendors only provide maximum power consumption values, while some others typical values.

We can also see in Fig. 9 that some specific power consumption values are more commonly used than others (the size of the marker is proportional to the number of works using that value). The most reported values may be good indicators of the actual power consumption of the devices. Nevertheless, they must be carefully assessed as the frequent occurrence of specific values might be explained by the reutilization of the only available values at the time of publication. Furthermore, some assumptions seem to be simply incorrect, particularly when comparing with the reference values from [302, 303].

The power consumption of an IP router is shown in Fig. 9(a). Comparing the power consumption of core routers is not an easy task since they are composed of several energy-consuming elements (e.g., router chassis, LCs with port cards, route processor, power supply, etc.). In general, power consumption of a router depends on its maximum capacity (i.e., maximum number of provided slots and the number of installed LCs). As can be noted, at high capacity (over 1 Tbps), the power consumption increases almost linearly with the capacity. In fact, at those capacities, the power consumption is increased due to the additional LCs that are installed to increase the capacity, but the contributions of other elements such as the chassis remain fairly constant with capacity. It is also worth mentioning that the big majority of reported power consumption values are based on the same references: the Cisco's CRS series and Juniper's T-series. Own measurements are rarely performed, and if so they concern usually devices of smaller capacities (with respect to core networking) [7]. It can be noticed in Fig. 9(a) that the power values assumed for high capacity routers are close to the reference values from [302][56].

Regarding the power consumption of LCs (Fig. 9(b)), we can observe relatively significant differences for devices of the same capacity. For instance, the reported power consumption values for a LC of 1 Gbps are in the range between 7.3 W and 1000 W. Being most of the reported values below 10 W, we can conclude that the value of 1000 W seems to be unrealistic and might certainly affect the achieved energy savings of any EA-ND or EA-NO approach. However, even the difference of 500 W between the two most commonly used power values of the 40 Gbps LCs (500 W and 1000 W) is significant. Nevertheless, assumptions made in the surveyed works are pretty close to the reference power models.

For the TSPs, we can clearly appreciate the improvements in terms of energy efficiency (in W/Gbps) when moving to higher capacities. For instance, a 400 Gbps TSP is able to quadruplicate the speed of a 100 Gbps TSP with slightly higher power consumption (at least in a similar range). Similar to the LCs, a considerably high difference can be found in the power consumption values of devices of the same type. In some cases, the difference on power consumption may come from the usage of different technologies. For example, coherent detection may be implemented in a 40 Gbps TSP to improve its performance (e.g., extended transmission reach), but will consume significantly more power than the conventional direct detection techniques. Furthermore, some values may include additional overhead contribution (e.g., cooling, power supply, etc.) which will definitely have an impact on the values. Nevertheless, the most frequently assumed power values are not far from the reference ones.

Finally, the power consumption values of OLAs are presented

[56]The power model of an IP router from [303] does not detail capacity.

TABLE XI
NUMBER OF SURVEYED APPROACHES.

Category	Optical	IP	IP & Optical	Total
EA-ND	22	8	30	60
EA-NO	21	65	11	97
Total	43	73	41	157

in Fig. 9(d). As for the rest of devices, a broad range of values can be found for OLAs. These variations could be explained by the fact that different types of amplifiers may be used (high-gain amplifiers will consume more than low-gain ones), or also depending on whether the overhead contributions are considered (e.g., controller card and fans) or not. Nevertheless, the assumption of 1000 W consumed by an OLA is an exaggeration, particularly when comparing to the reference values of 110 W [302] and 50 W [303] for OLAs with span equal to 80 km. The very low power values (less than 10 W), even if underestimating power consumption of OLAs (particularly with large spans), are more realistic regarding the actual amount of power that can be saved.

VI. DISCUSSION

In this work we analyzed over three hundred research articles on energy efficiency in core networks. Besides providing a wide picture of current state-of-art, our aim is to evaluate the whole activity presented in the last years on this topic, to highlight unsolved issues, and to suggest new directions for future works.

A first characterization of this work can be obtained analyzing the quantitative results shown in Table XI, where the number of surveyed approaches for each category is reported. The main outcome of the table is that in the EA-ND category there are many optical and combined IP/optical works, while in the EA-NO one there are mainly IP approaches and very few combined IP/optical ones (even taking into account the few approaches targeting devices in the IP layer but considering also the optical layer and its constraints). Considering that networks commonly operate in a multi-layer fashion, it is quite surprising that the largest part of operational approaches focus on a single layer, which may lead to unrealistic energy saving figures. On the one hand, the EA-NO approaches solely considering the IP layer can only provide a rough estimation of the energy savings since the constraints of the optical layer are usually neglected. On the other hand, the EA-NO approaches focusing on the optical layer provide rather realistic energy savings that can be obtained only in that layer. Therefore, considering (1) that today's networks operate in a multi-layer fashion, (2) that the IP layer is the most energy-hungry and flexible layer, and (3) the lack of EA-NO approaches covering both IP and optical layers and fulfilling all the evaluation criteria (i.e., mainly the last 9 columns of Table VII), we identify the combined IP/optical operational approaches being a potential (meaningful) contribution in the future.

In Fig. 10 we report a classification of EA approaches on the basis of four criteria: (1) layer, (2) line rate, (3) type of approach, and (4) performance evaluation methods. The clearest message of the figure is that there is a lack of testbed implementations. Simulation is the most commonly used tool for evaluation of EA approaches, while only few works focus on testbed implementation, thus suggesting that there is a gap between the proposed approaches and their practical realization. Energy savings are most frequently searched for in the IP layer (the most power-hungry one). SLR is most commonly assumed in the optical layer, while Mixed Line Rate (MLR) and elastic line rate are considered in a comparable

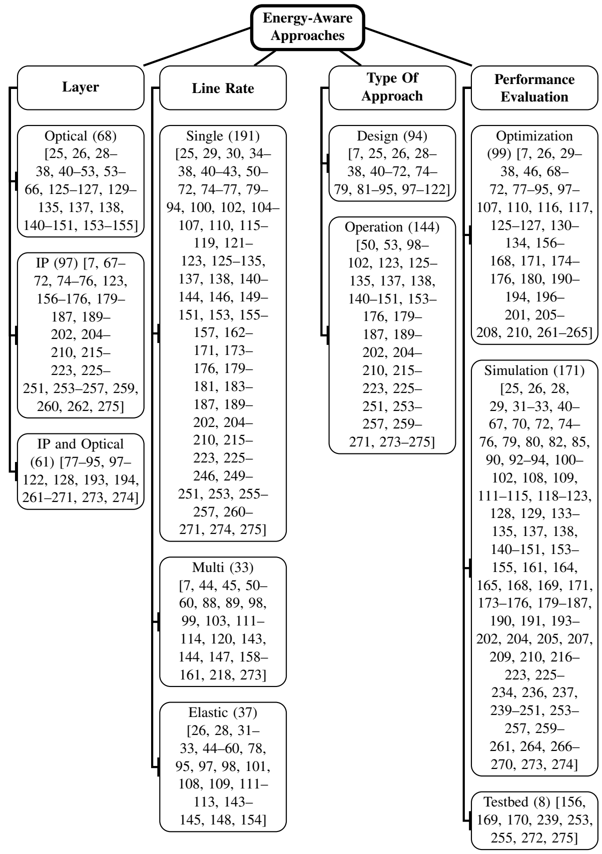


Fig. 10. Main Features of the Energy-Aware Approaches in Core Networks. Numbers in round brackets indicate the number of articles in each category. Concerning line rate, we assume that SLR is adopted unless multi or elastic line rate is mentioned. A single article may target several layers, cover several approaches, line rates, and evaluation methods.

number of works. Network operation is more frequently considered than network design. We point out the high number of EA-NO approaches for the IP layer (see Table XI). In the following subsections, we detail the main issues that may impact the implementation of sleep mode techniques in core networks.

A. Enabling Sleep Mode Approaches

To deeply understand the key parameters enabling EA core networks, we first review the main testbed implementations of approaches using sleep mode reviewed so far. In particular, in [239, 255] authors present the outcome of the Multi-(layer, path and resources) Dynamically Optimized Routing (MiDORi) project. The focus of the project is set on energy saving in the Gigabit Ethernet (GbE) network by selectively powering off network interfaces under hop-limit and bandwidth constraints. Powering on/off the whole transit routers or their parts is also considered. The authors demonstrate MiDORi on a fully meshed 6-node network testbed using Beeler's Algorithm (BA) with generic QoS restrictions.

Moreover, the work on CARISMA testbed is presented in [272]. The main idea of this work is to adopt GMPLS extensions in order to differentiate the power state of networking devices (such as TSP, LCs or REGs). The testbed is configured according to a Pan-European network composed of 16 nodes and 23 links with 10 bidirectional 100 Gbps TSPs per link, 20 add/drop TSPs per node, and 10 REGs. The experimental activities are restricted to protocol information exchanges.

In [275] the authors propose a practical implementation of the FUFL and Dynamic Upper Fixed Lower (DUFL) algorithms [194, 218]. In particular, the targeted devices are the optical GbE interfaces, with a network composed of three nodes and three links. In such scenario, the authors show that energy can be saved using off-the-shelf equipment not explicitly designed for dynamic on/off operation. Moreover, no packet loss is experienced during the experiments. However, the authors indicate the need for faster access to routers in order to perform the reconfiguration. This is particularly important for the more sophisticated energy saving approaches such as DUFL, since FUFL can be implemented locally.

Software routers are used in [169, 170] and [156]. Particularly, Netkit (emulation environment based on User-Mode Linux) is used in [169, 170] to reproduce the Abilene and Polska topologies [293] as well as an extended version of Abilene. Network node is represented by a virtual machine running the OSPF daemon Zebra, constant traffic generator Iperf, and the traffic monitor tool vnStat. MILP-based algorithm for Energy-aware Weights Optimization (MILP-EWO) is used to compute the EA link weights. Breakdown of a single link is also considered in order to study routing convergence time (less than a minute).

Similar approach is used in [156], even though implementation details are missing (except for Iperf used for traffic generation). GbE and Fast Ethernet (FE) cards are used to interconnect 7 software routers based on Linux Personal Computers (PCs). The authors point out that some traffic demands have to be reduced, because they would not fit into the network with reduced capacity due to energy saving. Furthermore, the measured power consumption is greater than the theoretically calculated one. This can be explained by additional activities of processors related to the tasks of traffic generation and measurements though.

Finally, the focus of [253] is to evaluate the routing protocol transients due to network reconfiguration, i.e., when passing from one TM to the following one. In particular, the authors propose Green Partial Exportation (GPE), an algorithm which is fully compatible with OSPF and target link power consumption. Moreover, a green software router which integrates GPE in the Quagga routing suite has been realized. The authors then define an experimental methodology to evaluate the effects of a green routing strategy on the network behavior in terms of delay and packet loss. Finally, GPE is evaluated on a testbed emulating a national telecom operator composed of 38 routers and 72 bidirectional links according to FT forecasts. The presented results show a maximum Round Trip Time (RTT) increase of 320 ms and a packet loss of 1.45% during the time in which the network is in transient state. Moreover, GPE can be safely applied in the network with a time granularity of less than a minute.

The lack of testbed implementations is also correlated with the unavailability of energy saving states for commercial network devices. Many of the surveyed EA-NO approaches have considered the availability of devices with “sleep mode” functionality. Such a device can switch from “on” to “sleep” state (and vice-versa), where a negligible amount of power is consumed and a very limited set of operative functionalities are available in the sleep state. The first consideration about this assumption is that, to the best of our knowledge, there is no current information of any commercial device for the core network implementing this feature. Moreover, the amount of time required for passing from one state to the other one is not considered, even if it can highly impact network performance. Finally, as a long-term objective, the realization of load proportional devices [306], i.e., devices able to adapt their operation according to the traffic conditions, could represent a significant step toward the deployment of an energy-efficient core network.

A further observation, resulting from the analysis of both EA-ND and EA-NO approaches, is that the knowledge of the TM is commonly assumed in many works. Traffic is actually a relevant parameter, which may have a significant impact on the potential energy savings of any EA approach. We recommend using traffic data originating from available measurements, even if, as mentioned in Section V-A, there is a lack of up-to-date realistic TMs. For this reason, many authors need to emulate the traffic conditions, which in many cases could be far from the real ones. A particular aspect that needs to be investigated is the influence of spatial traffic distribution on power saving. Traffic can vary over space e.g., due to different time zones in different parts of the globe [18, 93–96, 118, 307]. Traffic data originating from measurements spanning different time zones (particularly Abilene [292, 293]) captures the realistic variation of spatial traffic distribution. This behavior can be exploited by an energy saving approach to improve its performance. None of the surveyed papers analyzed this aspect in the context of power saving achieved with the EA-NO approaches.

B. QoS evaluation metrics

The possibility of implementing an EA approach in operational networks strictly depends on its impact on network performance. In order to analyze how the proposed approaches impact this aspect, we report in Table XII the QoS evaluation metrics used in surveyed approaches, ranked on the basis of their popularity. As expected, the most common metric is the Link/Node Utilization. This metric assures that the specific EA approach avoids packet loss or maintains a residual available bandwidth for unexpected peak periods. A similar parameter for the characterization of the performance in a dynamic scenario (typically in the optical layer) is the blocking probability. The reconfiguration cost is instead related to the modifications caused by the specific EA approach to the network configuration: a typical reconfiguration cost may be the amount of traffic involved by path modification or the number of network device power state changes involved by the reconfiguration. Path length is the last widely considered QoS metric. This topological parameter is strictly related to the end-to-end delay experienced by users. Additionally, the direct evaluation of the delay (the propagation delay metric) is considered in fewer works.

Regarding the other metrics reported in Table XII, we point out that a limited number of approaches directly evaluate protection-related QoS metrics, such as average number of disjoint paths, protection switching time, restored traffic upon a link failure, average number of secondary paths, and single link-failures that would disconnect (parts of) the network.

A very important effect of EA approaches (for implementation reasons) to be considered is the network transient, i.e., the time period required by the network to pass between two consecutive network configurations. The network transient may result in undesirable effects for the network, such as path unavailability and routing loops. Consequently network performance can be significantly degraded during the transient period. The only work we found about this aspect is [253], where the routing protocol transients due to network reconfiguration are studied in terms of RTT variation. We strongly believe that the network transient caused by EA approaches should be more extensively investigated in the future.

TABLE XII
QoS EVALUATION METRICS FOR ENERGY-AWARE SOLUTIONS IN CORE NETWORKS.

No.	Metric	No. of Papers	References
1	Link/Node utilization	61	[37, 72, 77, 98, 137, 138, 153, 156, 162–170, 173–175, 179–181, 184–187, 189, 193, 194, 197–202, 204–210, 215, 220, 222, 225, 234, 235, 242, 243, 245–247, 250, 251, 256, 257, 260, 263, 264]
2	Path length	31	[70, 72, 105, 135, 138, 140, 141, 186, 191, 192, 197–201, 220, 233, 234, 242–244, 248–250, 253, 266–271]
3	Blocking probability	30	[40, 47–54, 56–60, 135, 137, 138, 140, 141, 145, 147, 153, 215, 241, 261, 266, 267, 269, 271, 273]
4	Reconfiguration costs	30	[158–160, 162–164, 171, 175, 186, 187, 189, 195, 196, 216, 223, 230, 232–234, 236, 237, 240, 241, 244–246, 253, 262, 265, 275]
5	Propagation delay	9	[71, 92–94, 121, 161, 174, 185, 208]
6	Network overload	9	[71, 189, 195, 230, 232, 236, 237, 246, 253]
7	Mean transit traffic	5	[196, 216, 240, 247, 275]
8	Link/Lightpath signal quality	3	[65, 66, 125]
9	Maximum link utilization variation	3	[137, 138, 209]
10	Number of transitions leading to congestion	3	[189, 245, 246]
11	Average number of disjoint paths	3	[197–199]
12	Number of used fibers on each link	2	[135, 155]
13	Fairness of traffic distribution over links	2	[138, 250]
14	Protection switching time	2	[119, 130]
15	Restored traffic upon a link failure	1	[71]
16	Connectivity/Route reliability	1	[207]
17	Queue length	1	[161]
18	Max. logical link utilization	1	[161]
19	Avg. number of secondary paths traversing a sleep link	1	[137]
20	Single-link failures that would result in a disconnected network	1	[71]
21	RTT variation	1	[253]

C. *Future research directions*

Energy efficiency has been a hot research topic during the last 5 years. The challenge for the future is to provide implementable approaches and to evaluate their effects on a long-term time scale. For this reason we detected three main trends for the upcoming research in this area: (1) EON, (2) SDN, and (3) device lifetime.

Elastic Optical Networks: The EON paradigm opens new doors for future research at different levels of optical networks. One of the promising functionalities foreseen for EON is the adaptation of the transmission to different traffic conditions by expanding/contracting the bandwidth and/or increasing/decreasing the modulation order. The traffic rate adaptation will offer a great potential to improve the energy efficiency of core networks. Despite the recent publications of different EA approaches (summarized in Sections III and IV), the research area of EA EON remains a relatively unexplored field. Nevertheless, it is worth mentioning that many of the reported EA approaches for conventional WDM networks (e.g., sleep mode approaches for WDM) could also be extended to EON. The operation of EON relies on novel bandwidth-variable network elements (i.e., BV-TSP and BV-OXC). In particular, further work is required to develop BV-TSP based on multicarrier structures with more advanced modulation formats and dynamic transmission adaptation. Accordingly, obtaining reliable information on power consumption values is still one of the main difficulties for the energy-efficient research related to EON. Most of the power consumption models used for EON in the literature are based on simple assumptions. Moreover, the impact on QoS and physical layer constraints might be significantly more complex than for conventional WDM networks. These aspects must be carefully assessed for the EA-NO approaches in order to make the reconfiguration of the optical layer transmission “hitless” (or with negligible impact). In what concerns the control mechanisms, EON will also need more advanced approaches to fully exploit its advantages such as TSP configurability as well as spectral assignment flexibility (including spectral defragmentation techniques). In this regard, the impact of the application of these techniques on the control mechanisms must also be carefully assessed. The flexibility provided by EON can also be useful to exploit novel survivability techniques that can reduce power consumption with respect to the conventional protection schemes such as DPP and SPP.

Software Defined Networking: The availability of an intelligent control plane becomes a key for the reconfiguration of the network and the realization of EA-NO approaches. For instance, new control plane extensions for GMPLS signaling and routing protocols as well as the Path Computation Element (PCE) may be necessary. Energy efficiency might be taken into account in the EA algorithms run at the PCE such as Open Shortest Path First-Traffic Engineering (OSPF-TE). Nodes will have to disseminate information about energy consumption. This is not done in the current OSPF implementations. Moreover, different approaches consider the optimization of energy efficiency in a multi-layer fashion, thus requiring an advanced multilayer control plane to realize the interaction between the routing and the transmission part. The SDN paradigm is seen as a disruptive technology to provide significant benefits for the operators and users by means of increased flexibility and more efficient utilization of resources. SDN assumes that the control plane (software) will be decoupled from the physical topology (hardware), while they are coupled together in current networks. This concept is expected to significantly increase the flexibility of the network. SDN is still in a development stage, but its benefits have already been proven in data center environments [308]. In the core network, the so-called transport SDN will allow to integrate new control plane functionalities in an easier way, simplifying the deployment of EA-NO approaches in real network scenarios. However, the use of programmable forwarding devices (i.e., SDN switches) will introduce new constraints to be considered when formalizing the EA-NO problem. In particular, the use of expensive and power-

TABLE XIII
CANDIDATE APPROACHES FOR ENERGY-AWARE CORE NETWORKS.

Type	Layer	Method's Name	Motivation
Design	Optical	PARD [40]	Efficient heuristic for reliable network design targeting multiple types of devices to be powered off and considering installation of fibers.
Design	IP	DEL [67]	A heuristic making use of a MILP formulation and considering protection.
Design	IP & Optical	MILP [86]	An efficient MILP formulation covering all criteria for IP-over-WDM but WA (which can be done in postprocessing).
Operation	Optical	PA-RWA (LBC & LCW) [135]	Quick and distributed approach combining routing algorithm LBC and WA algorithm LCW with smart functions computing link weights.
Operation	IP	DAISIES [234]	Quick and distributed adaptive approach using smart functions computing link weights and fulfilling all criteria but protection (limited impact on QoS shown).
Operation	IP & Optical	DAISIES + PA-RWA [128]	Combination of the approach in the IP layer passed to the approach in the WDM layer.

hungry Ternary Content-Addressable Memories (TCAMs) for the forwarding tables will require to minimize the rules installed on each SDN switch [200].

Lifetime-Aware Networks: Another point that sleep mode approaches should take into account is their impact on the device lifetime [211, 309]. More in depth, when a sleep mode state is set, the temperature of the device is decreased, since the largest part of its circuits can be powered off. According to studies that have been performed on Central Processing Units (CPUs) and memories [310], the lower the temperature, the lower also the probability of a failure event. Thus, if the temperature decrease is the only effect taken into consideration, sleep mode would increase the device lifetime. However, also the variation of temperature (introduced when passing from sleep mode to fully operational state) has an impact on the lifetime. In particular, in [311] authors report temperature measurements of disks, memories, and components in data centers showing that the largest impact on failure rates is due to the variation of temperature rather than the increase of temperature. More in depth, the higher the number of induced power cycles, the higher the reduction in the device lifetime [312]. Thus, we can see that there are two opposite effects triggered by the application of sleep mode [313]: one positive (decrease of temperature) and one negative (variation of temperature). Therefore, the application of sleep mode approaches may not be beneficial to the lifetime, due to the fact that the benefits of energy savings may be surpassed by the increase in the failure rate of the devices [211]. We therefore envision future algorithms able to balance energy-savings and lifetime of the network devices, as well as a deep investigation of lifetime models in energy-aware networks. Additionally, another research activity should be the comparison of the monetary savings introduced by energy-savings with the reparation costs triggered by failures, in order to define algorithms able to trade between these two features.

VII. CONCLUSION

We have proposed a survey of the EA approaches in core networks. We consider works targeting either the design or operation stages, and considering one (IP or optical) or two layers. We have provided a detailed characterization of the optimization problems raising in the field, as well as a taxonomy to classify the different EA approaches. Interestingly, we have found many works covering both layers during the design step, while very few works consider a multi-layer network during the operation phase. A joint approach seems to be the best candidate to achieve high energy-saving while guaranteeing an adequate QoS for users.

In the light of the main features, we propose candidates for EA networks summarized in Table XIII, and support them with a single (the most representative in our opinion) reference. Network design is a complex process, and sophisticated approaches (such as the MILP [86] for the IP and optical layers) are desirable. On the contrary, low complexity and distributed approaches are welcome in network operation, even though they are not expected to bring the highest energy savings. A comparative evaluation study of several EA-NO approaches over the same network scenario can be found in [123].

We have shown in this work that finding realistic network instances (especially in terms of spatial and temporal traffic) is an open issue, since most of the approaches consider realistic topologies, but only few of them take into account realistic (and up-to-date) TMs. Additionally, we have shown that different assumptions on power consumption values of single devices are made. We observed in few cases significant discrepancy from the reference power models proposed in the literature. Nevertheless, clear trends toward realistic parametrization can be seen, particularly for TSPs and LCs. We confirmed (based on these trends) the observations that power consumed by devices tends to be proportional to their installed capacities, and that devices of higher capacities are more energy-efficient in terms of W/bps (or its inverse, neglecting the actual throughput).

As future works, we have highlighted the need of more effective standardization efforts to introduce sleep mode capabilities into real network devices and to enhance control protocols features. In particular the adoption of SDN and EON can speed up the practical implementation of energy-efficient approaches. Additionally, a radical improvement in the testbed implementations is needed, in order to provide a full characterization of EA approaches, in terms of both performance and implementation issues. Finally the impact of sleep mode on the device lifetime should be studied, to avoid the increase of the devices replacement costs in the long-term, what can frustrate the operational energy savings.

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LIST OF ACRONYMS

3-ShP-FF 3 first Shortest Paths–First Fit
A-ESR Ant colony optimization based Energy Saving Routing
ADD ADDing edges algorithm
AGA Alternative Greedy Algorithm
ALR Adaptive Link Rate

AMS-IX	AMSterdam Internet Exchange
ARIMA	Auto Regressive Integrated Moving Average
AS	Autonomous System
ASM	Adaptive Sleep Mode
ASON	Automatically Switched Optical Network
ATD	Adaptive Traffic Distribution
AUR-E	Adaptive Unconstrained Routing Exhaustive
AWG	Arrayed Waveguide Grating
BA	Beeler's Algorithm
B-EMP	Best Enhanced Most Power
B-E2SIR	Best Enhanced Energy Saving IP Routing
BFS	Breadth-First-Search
BV-OXC	Bandwidth Variable OXC
BV-TSP	Bandwidth Variable TranSPonder
CO-OFDM	Coherent Optical Orthogonal Frequency Division Multiplexing
CPEEM	Cost and Power savings algorithm based on End-to-End waveband Merging
CPSPM	Cost and Power savings algorithm based on Sub-Path waveband Merging
CPU	Central Processing Unit
CS	Circuit Switching
DAISIES	Distributed and Adaptive Interface Switch off for Internet Energy Saving
DBF	Destination Based Forwarding
DEMUX	DEMUltipleXer
DEER	Distributed Energy-Efficient Routing
DEL	DELeting Edges algorithm
DELM	Distributed Energy-Aware Link Management
DFN	Deutsches ForschungsNetz
DGA	Dijkstra Green Advanced
DGB	Dijkstra Green Baseline
DiPP	Disjoint Path Protection
DiR	Differentiated Reliability
DLF	Distributed Least Flow
DLH	Direct Lightpath Heuristic
DLP	Dedicated Link Protection
DMP	Distributed Most Power
DON	Dynamic Optical Node
DPP	Dedicated Path Protection
DP TAPA	Dedicated Protection Traffic-Aware Power-Aware
DSA	Depth-d Search Algorithm
DUFL	Dynamic Upper Fixed Lower
E2SR	Energy-Efficient and Survivable Routing
EA	Energy-Aware
EA-DPP	Energy-Aware Dedicated Path Protection
EA-DPP-Dif	Energy-Aware Dedicated Path Protection with Differentiation of primary and secondary paths
EA-DPP-MixS	Energy-Aware Dedicated Path Protection with Mixing Secondary with primary paths
EA-LG	Energy-Aware Lexicographic Greedy randomized adaptive search procedure
EA-ND	Energy-Aware Network Design
EA-NO	Energy-Aware Network Operation
EA-RMLSA	Energy-Aware Routing, Modulation Level and Spectrum Allocation
EA-RWA	Energy-Aware Routing and Wavelength Assignment
EASPP	Energy-Aware Shared Path Protection
EA-STH	Energy-Aware Single Time-period Heuristic
EAAG	Energy-Aware Auxiliary Graph
EAR	Energy-Aware Routing
EAR-SDN-MILP	Energy-Aware Routing Software Defined Networking MILP
EAR-SDN-H	Energy-Aware Routing Software Defined Networking Heuristic
EDFA	Erbium Doped Fiber Amplifier
EE	Energy-Efficient
EE-FON	Energy-Efficient Flexible Optical Network
EEM	End-to-End waveband Merging
EEPG	Energy Efficiency Per GHz
EET	Energy-Efficient Topology
E-MIN	Emission minimized route with MINum number of lightpaths
EON	Elastic Optical Network
E-PRO	Emission minimized route with PROactive green lightpaths
ESA-STH	Energy and Survivability Aware Single Time-period Heuristic
ESIR	Energy Saving IP Routing
ESACON	Energy Saving based on Algebraic CONnectivity
ESOL	Energy Saving based on Occurrence of Links
ES-ROD	Energy Saving Routing On Demand
ESTOP	Energy Saving based on TOPology control
EWA	Energy Watermark Algorithm
E2-MCRA	Energy-Efficient Multi Constrained Routing Algorithm
FE	Fast Ethernet
FF	First Fit
FUFL	Fixed Upper Fixed Lower
GA	Genetic Algorithm
GAGD	Genetic Algorithm for Green Design
GAPS	Greedy Algorithm for Power Saving
GBDA	Greedy Based Distributed Algorithm
GBP	Green Backup Paths
GbE	Gigabit Ethernet
GDRP-PS	General Distributed Routing Protocol for Power Saving
GEH	Green Elimination Heuristic
GGA	Green Grooming Algorithm
GLA	Green Load-balancing Algorithm
GLGA	GLobal Greedy Algorithm
GMPLS	Generalized MultiProtocol Label Switching
GPE	Green Partial Exportation
GreenFRR	Green Fast ReRouting
GreenTE	Green Traffic Engineering
GRiDA	GReen Distributed Algorithm
GVN	Green Virtual Network
H-GreenRE	Heuristic for Green Redundancy Elimination
HEER	Heuristic for Energy Efficient Routing
HCTG	Heaviest-first and Comparison Traffic Grooming
HOCTG	HOttest-first and Comparison Traffic Grooming
HS	Harmonic Series
ICT	Information and Communication Technology
IGH	IP-Grooming Heuristic
ILP	Integer Linear Programming
ILPFSD	Integer Linear Programming Fixed-window Scheduling Demands
ILPSSD	Integer Linear Programming Sliding-window Scheduling Demands
IP	Internet Protocol
ISFO	Iterative Switching Fibers Off
ISIS	Intermediate System to Intermediate System
IT	Information Technology
ITU-T	International Telecommunication Union –

	Telecommunication standardization sector
KShP	K-Shortest Paths
LAP	Link Addition type Power-saving topology construction
LBC	Load Based Cost
LBG	Lightpath-Based Grooming
LC	Line Card
LCP	Least-Cost Path
LCW	Least Cost Wavelength
LE-I	Less Energy Incremental
LFA	Least Flow Algorithm
LLEH	Least Loaded Edge Heuristic
LLN	Least Loaded Node
LNF	Lightest Node First
LR	Lagrangian Relaxation
LR&HS	Lagrangian Relaxation and Harmonic Series
LDB	Least Diversion Blind
LDM	Least Diversion Matrix
LSA	Link State Advertisement
LT	Logical Topology
LTD	Logical Topology Design
LTL	Least Traversed Link
LUB	Link Utilization Based
MEMS	Micro Electro-Mechanical System
MFA	Mini Fiber Algorithm
MG-OTN	Multi-Granular Optical Transport Network
MH/SOH	Multi-Hop/Successive One Hop
MH/ST	Multi-Hop/SinkTree
MiDORi	Multi-(layer, path and resources) Dynamically Optimized Routing
MILP	Mixed-Integer Linear Programming
MILP-EWO	MILP-based algorithm for Energy-aware Weights Optimization
MILP-MMF	MILP Maximum Min Fairness
MILP	Mixed-Integer Linear Programming
MINLP	Mixed-Integer NonLinear Programming
MLR	Mixed Line Rate
MLTE	MultiLayer Traffic Engineering
MPA	Most Power Algorithm
MPR	Multi-Path Routing
MPLS	MultiProtocol Label Switching
MP-S	Minimum Power with Sleep mode support
MRP	Mixed Regenerator Placement
MSGPE	Multi-hop Survivable Grooming for Power Efficiency
MUP	Most-Used Path
MUX	MUltipleXer
MXHF	MaXimizing Hop First
NIC	Network Interface Card
NMS	Network Management System
OEO	Optical-Electrical-Optical
OFDM	Orthogonal Frequency Division Multiplexing
OH/AS	One-Hop/Aggressive Setup
OH/CS	One-Hop/Conservative Setup
OLA	Optical Line Amplifier
OLMUP	Ordered-Lightpath Most-Used Path
OPG	Optimal Port Grouping
OSPF	Open Shortest Path First
OSPF-TE	Open Shortest Path First-Traffic Engineering
OTN	Optical Transport Network
OXC	Optical Cross-Connect
PA	Power-Aware
PAR	Power Aware Routing
PARD	Power-Aware Reliable Design
PA-RWA	Power-Aware Routing and Wavelength Assignment
PAFRP	Power-Aware Fixed Routing Problem
PASPP	Power-Aware Shared Path Protection
PAVRP	Power-Aware Variable Routing Problem
PC	Personal Computer
PCE	Path Computation Element
P-EER	Pure Energy Efficient Routing
PIR	Power-efficient Integrated Routing
PIRTS	Power-efficient Integrated Routing with Traffic Splitting
P-MIN	Power minimized route with MINimum number of lightpaths
PMH	PAR Meta Heuristic
P-PRO	Power minimized route with PROactive green lightpaths
PS	Packet Switching
QA-EER	QoT Aware Energy Efficient Routing
QoP	Quality of Protection
QoS	Quality of Service
QoT	Quality of Transmission
RB	Relieved Blind
RDB	Red-Demand-Based
RE	Redundancy Elimination
REG	REGenerator
REO-hop	Renewable Energy Optimization hop
R-GR	Reliable Green Routing
RH	Random Heuristic
RL	Rollback Last
RM	Relieved Matrix
RMLSA	Routing, Modulation Level and Spectrum Allocation
RPH	Restricted Path Heuristic
RPP-SP	Routing with Power down Problem based on Shortest Path
RPP-T	Routing with Power down based on Tree
RR	Route Reliability
RSA	Routing and Spectrum Allocation
RSB	Request Size Based
RSTA	Routing STandby Algorithm
RTT	Round Trip Time
RWA	Routing and Wavelength Assignment
RX	Receiver
SAA	Simulated Annealing Algorithm
SAAPP	Simulated Annealing Algorithm with Post Processing
SBN	Static Base Network
SDH	Synchronous Digital Hierarchy
SDN	Software Defined Networking
ShP-FF	Shortest Path–First Fit
ShPR	Shortest Path Routing
SLP	Shared Link Protection
SLR	Single Line Rate
SM	Sleep Mode
SMA-GMPLS	Sleep Mode Aware Generalized MultiProtocol Label Switching
SPM	Sub-Path waveband Merging
SPP	Shared Path Protection
SPR	Single-Path Routing
SR	Short Reach
SSGPE	Single-hop Survivable Grooming considering Power Efficiency
Start-SH&ReR	Start Single-Hop and Reroute
STPH	Single Time Period Heuristic

STPH-RP	Single Time Period Heuristic - Restricted Path
TATG	Time-Aware Traffic-Grooming
TAP-BR	Time-Aware Provisioning with Bandwidth Reservation
TCAM	Ternary Content-Addressable Memory
TCP	Transmission Control Protocol
TDB	Total-Demand-Based
TDGTG	Two-Dimension Green Traffic Grooming
TDS	Time Driven Switching
TLB	Table Lookup Bypass
TLPH	Time Limited PAR Heuristic
TLS	Time-driven Link Sleeping
TLS-SLFP	Time-driven Link Sleeping Single Link Failure Protection
TM	Traffic Matrix
TX	Transmitter
TR	Terminal Reliability
TSP	TranSPonder
VLCM	Virtual Line Card Migration
VTCR	Virtual Topology Centric Reconfiguration
WA	Wavelength Assignment
WDM	Wavelength Division Multiplexing
WLCT	WaveLength ConverTer
WPA-LR	Weighted Power-Aware Lightpath Routing

REFERENCES

[1] L. Neves, S. Howard *et al.*, "Smart 2020 report - enabling the low carbon economy in the information age," The Climate Group, 2008.

[2] V. Rozite, "Network standby towards a policy framework," https://www.iea.org/media/workshops/2013/networkedstandby/1RoziteINTRO2013NetworkStandby.pdf, International Energy Agency, Mar. 2013.

[3] S. Pileri, "Energy and communication: engine of the human progress," in *Proc. INTELEC, Rome, Italy*, Sep. 2007.

[4] M. Etoh, T. Ohya, and Y. Nakayama, "Energy consumption issues on mobile network systems," in *Proc. SAINT, Turku, Finland*, July 2008.

[5] J. F. Kurose, *Computer networking: a top-down approach featuring the Internet*. Pearson Education, 2005.

[6] A. M. Odlyzko, "Data networks are mostly empty and for good reason," *Review of Network Economics*, vol. 2, no. 3, pp. 210–237, Sep. 2003.

[7] J. Chabarek, J. Sommers, P. Barford, C. Estan, D. Tsiang, and S. Wright, "Power awareness in network design and routing," in *Proc. INFOCOM, Phoenix, USA*, Apr. 2008.

[8] M. Gupta and S. Singh, "Greening of the Internet," in *Proc. SIGCOMM, Karlsruhe, Germany*, Aug. 2003.

[9] A. P. Bianzino, C. Chaudet, D. Rossi, and J.-L. Rougier, "A survey of green networking research," *IEEE COMST*, vol. 14, no. 1, pp. 3–20, First Quarter 2012.

[10] R. Bolla, F. Davoli, R. Bruschi, K. Christensen, F. Cuchietti, and S. Singh, "The potential impact of green technologies in next-generation wireline networks: Is there room for energy saving optimization?" *IEEE ComMag*, vol. 49, no. 8, pp. 80–86, Aug. 2011.

[11] W. Van Heddeghem, F. Idzikowski, E. Le Rouzic, J. Y. Mazeas, H. Poignant, S. Salaun, B. Lannoo, and D. Colle, "Evaluation of Power Rating of Core Network Equipment in Practical Deployments," in *Proc. greencom, online conference*, Sep. 2012.

[12] Y. Zhang, P. Chowdhury, M. Tornatore, and B. Mukherjee, "Energy efficiency in telecom optical networks," *IEEE COMST*, vol. 12, no. 4, pp. 441–458, Fourth Quarter 2010.

[13] R. Bolla, R. Bruschi, F. Davoli, and F. Cucchietti, "Energy efficiency in the future Internet: A survey of existing approaches and trends in energy-aware fixed network infrastructures," *IEEE COMST*, vol. 13, no. 2, pp. 223–244, Second Quarter 2011.

[14] M. N. Dharmaweera, R. Parthiban, and Y. A. Şekercioğlu, "Towards a power-efficient backbone network: The state of research," *IEEE COMST*, vol. 17, no. 1, pp. 198–227, First Quarter 2015.

[15] A.-C. Orgerie, M. D. d. Assuncao, and L. Lefevre, "A survey on techniques for improving the energy efficiency of large-scale distributed systems," *ACM CSUR*, vol. 46, no. 4, pp. 47:1–47:31, Mar. 2014.

[16] W. Van Heddeghem, B. Lannoo, D. Colle, M. Pickavet, and P. Demeester, "A quantitative survey of the power saving potential in IP-over-WDM backbone networks," *IEEE COMST*, 2014, in press, available online.

[17] M. Fiorani, M. Casoni, and S. Aleksić, "Hybrid optical switching for energy-efficiency and qos differentiation in core networks," *IEEE/OSA JOCN*, vol. 5, no. 5, pp. 484–497, May 2013.

[18] X. Dong, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Green IP over WDM networks with data centers," *IEEE/OSA JLT*, vol. 29, no. 12, pp. 1861–1880, June 2011.

[19] A. Q. Lawey, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Distributed energy efficient clouds over core networks," *IEEE/OSA JLT*, vol. 32, no. 7, pp. 1261–1281, Apr. 2014.

[20] N. I. Osman, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Caching in green IP over WDM networks," *IOS JHSN*, vol. 1, no. 19, pp. 33–53, Mar. 2013.

[21] L. Hao, W. Hou, L. Guo, and X. Wang, "Multicast grooming algorithm in green IP over WDM networks," in *Proc. ICCTD, Cairo, Egypt*, Nov. 2010.

[22] N. Vasić and D. Kostić, "Energy-aware traffic engineering," School of Computer and Communication Sciences, École polytechnique fédérale de Lausanne, Tech. Rep. NSL-REPORT-2008-004, 2008.

[23] ——, "Energy-aware traffic engineering," in *Proc. e-Energy, Passau, Germany*, Apr. 2010.

[24] O. Gerstel, M. Jinno, A. Lord, and S. J. B. Yoo, "Elastic optical networking: a new dawn for the optical layer?" *IEEE ComMag*, vol. 50, no. 2, pp. S12–S20, Feb. 2012.

[25] Y. Wu, L. Chiaraviglio, M. Mellia, and F. Neri, "Power-aware routing and wavelength assignment in optical networks," in *Proc. ECOC, Vienna, Austria*, Sep. 2009.

[26] A. Nag, T. Wang, and B. Mukherjee, "Robust design of spectrum-efficient green optical backbone networks," *IEEE/OSA JLT*, vol. 31, no. 7, pp. 1138–1144, Apr. 2013.

[27] A. Nag, M. Tornatore, and B. Mukherjee, "Energy-efficient and cost-efficient capacity upgrade in mixed-line-rate optical networks," *IEEE/OSA JOCN*, vol. 4, no. 12, pp. 1018–1025, Dec. 2012.

[28] H. Khodakarami, B. S. G. Pillai, B. Sedighi, and W. Shieh, "Flexible optical networks: An energy efficiency perspective," *IEEE/OSA JLT*, vol. 32, no. 21, pp. 3356–3367, Nov. 2014.

[29] G. Shen, W. Shao, and L. Peng, "Green optical channel layer design with minimum use of optical amplifiers and fibers," in *Proc. ICOCN, Guangzhou, China*, Nov. 2011.

[30] Ç. Çavdar, F. Buzluca, and L. Wosinska, "Energy-efficient design of survivable WDM networks with shared backup," in *Proc. GLOBECOM, Miami, USA*, Dec. 2010.

[31] X. Chen, F. Ji, Y. Wu, and Z. Zhu, "Energy-efficient resilience in translucent optical networks with mixed regenerator placement," *IEEE/OSA JOCN*, vol. 5, no. 7, pp. 741–750, July 2013.

[32] X. Chen, F. Ji, and Z. Zhu, "Energy-efficient protection designs for translucent optical networks using mixed regenerator placement," in *Proc. OFC, Anaheim, USA*, Mar. 2013.

[33] Z. Zhu, X. Chen, F. Ji, L. Zhang, F. Farahmand, and J. P. Jue, "Energy-efficient translucent optical transport networks with mixed regenerator placement," *IEEE/OSA JLT*, vol. 30, no. 19, pp. 3147–3156, Oct. 2012.

[34] A. Muhammad, P. Monti, I. Cerutti, L. Wosinska, P. Castoldi, and A. Tzanakaki, "Energy-efficient WDM network planning with dedicated protection resources in sleep mode," in *Proc. GLOBECOM, Miami, USA*, Dec. 2010.

[35] A. Tzanakaki, M. Anastasopoulos, K. Georgakilas, J. Buysse, M. De Leenheer, C. Develder, S. Peng, R. Nejabati, E. Escalona, D. Simeonidou, N. Ciulli, G. Landi, M. Brogle, A. Manfredi, E. López, J. Ferrer Riera, J. Garcia-Espin, P. Donaldio, G. Parladori, J. Jiménez, A. Tovar De Duenyas, P. Vicat-Blanc, J. Van der Ham, C. De Laat, M. Ghijsen, B. Belter, A. Binczewski, and M. Antoniak-Lewandowska, "Energy efficiency considerations in integrated IT and optical network resilient infrastructures," in *Proc. ICTON, Stockholm, Sweden*, June 2011.

[36] A. Tzanakaki, M. Anastasopoulos, K. Georgakilas, J. Buysse, M. De Leenheer, C. Develder, S. Peng, R. Nejabati, E. Escalona, D. Simeonidou, N. Ciulli, G. Landi, M. Brogle, A. Manfredi, E. López, J. Riera, J. Garcia-Espin, P. Donadio, G. Parladori, and J. Jiménez, "Energy efficiency in integrated IT and optical network infrastructures: The GEYSERS approach," in *Proc. INFOCOM Workshop on Green Communications and Networking, Shanghai, China*, Apr. 2011.

[37] A. Tzanakaki, M. Anastasopoulos, G. Konstantinos, S. Peng, R. Nejabati, E. Escalona, and D. Simeonidou, *Energy Efficient VI Planning over Converged Optical Network and IT Resources*. CRC Press, Sep. 2012, ch. 25, pp. 719–740.

[38] R. M. Morais, J. Pedro, P. Monteiro, and A. N. Pinto, "Impact of node architecture in the power consumption and footprint requirements of optical transport networks," *IEEE/OSA JOCN*, vol. 5, no. 5, pp. 421–436, May 2013.

[39] A. Tzanakaki, K. Katrinis, T. Politi, A. Stavdas, M. Pickavet, P. Van Daele, D. Simeonidou, M. J. O'Mahony, S. Aleksić, L. Wosinska, and P. Monti, "Dimensioning the future Pan-European optical network with energy efficiency considerations," *IEEE/OSA JOCN*, vol. 3, no. 4, pp. 272–280, Apr. 2011.

[40] B. Kantarci and H. Mouftah, "Greening the availability design of optical WDM networks," in *Proc. GLOBECOM Workshop on Green Communications, Miami, USA*, Dec. 2010.

[41] S. S. Jalalinia, Ç. Çavdar, and L. Wosinska, "Survivable green optical backbone networks with shared path protection," in *Proc. OFC, Los Angeles, USA*, Mar. 2012.

[42] M. Xia, M. Tornatore, Y. Zhang, P. Chowdhury, C. Martel, and B. Mukherjee, "Green provisioning for optical WDM networks," *IEEE JSTQE*, vol. 17, no. 2, pp. 437–445, Mar./Apr. 2011.

[43] ——, "Greening the optical backbone network: A traffic engineering approach," in *Proc. ICC, Cape Town, South Africa*, May 2010.

[44] E. Palkopoulou, M. Angelou, D. Klonidis, K. Christodoulopoulos, A. Klekamp, F. Buchali, E. Varvarigos, and I. Tomkos, "Quantifying spectrum, cost, and energy efficiency in fixed-grid and flex-grid networks," *IEEE/OSA JOCN*, vol. 4, no. 11, pp. B42–B51, Nov. 2012.

[45] M. Angelou, K. Christodoulopoulos, D. Klonidis, A. Klekamp, F. Buchali, E. Varvarigos, and I. Tomkos, "Spectrum, cost and energy efficiency in fixed-grid and flex-grid networks," in *Proc. OFC, Los Angeles, USA*, Mar. 2012.

[46] Y. Wu, W. Hou, L. Guo, Y. Liu, and Z. Sun, "Green grooming in elastic optical networks," in *Proc. OFC, San Francisco, USA*, Mar. 2014.

[47] J. López Vizcaíno, Y. Ye, F. Jiménez, A. Macho, and P. M. Krummrich, "Increased energy-efficiency and capacity for Mixed-Line-Rate WDM networks with hybrid Raman-EDFA amplification," in *Proc. ECOC, Cannes, France*, Sep. 2014.

[48] J. López Vizcaíno, Y. Ye, F. Jiménez, and P. M. Krummrich, "Amplifier placements optimization for enhanced energy efficiency in optical transport networks," in *Proc. ICC, Sydney, Australia*, June 2014.

[49] J. López Vizcaíno, Y. Ye, F. Jiménez, A. Macho, and P. M. Krummrich, "Optimized amplifier placements for improved energy and spectral efficiency in protected mixed-line-rate networks," in *Proc. OFC, San Francisco, USA*, Mar. 2014.

[50] J. López Vizcaíno, Y. Ye, F. Jiménez, R. Duque, I. Tafur Monroy, and P. M. Krummrich, *Energy Efficiency Improvement with the Innovative Flexible-Grid Optical Transport Network*. CRC Press, Oct. 2013, ch. 17, pp. 397–432.

[51] J. López Vizcaíno, Y. Ye, and I. Tafur Monroy, "Energy efficiency analysis for flexible-grid OFDM-based optical networks," *Elsevier ComNet*, vol. 56, no. 10, pp. 2400–2419, July 2012.

[52] J. López Vizcaíno, Y. Ye, and I. Monroy, "Energy efficiency in elastic-bandwidth optical networks," in *Proc. NOF, Paris, France*, Nov. 2011, pp. 107–111.

[53] J. López Vizcaíno, Y. Ye, V. López, F. Jiménez, F. Musumeci, M. Tornatore, A. Pattavina, and P. M. Krummrich, "Protection in optical transport networks with fixed and flexible grid: Cost and energy efficiency evaluation," *Elsevier OSN*, vol. 11, no. Part A, pp. 55–71, 2014.

[54] J. López Vizcaíno, Y. Ye, V. López, F. Jiménez, R. Duque, and P. M. Krummrich, "Cost evaluation for flexible-grid optical networks," in *Proc. GLOBECOM Workshop on Flexible Optical Networks, Atlanta, USA*, Dec. 2012, pp. 358–363.

[55] ——, "On the energy efficiency of survivable optical transport networks with flexible-grid," in *Proc. ECOC, Amsterdam, The Netherlands*, Sep. 2012.

[56] J. López Vizcaíno, Y. Ye, F. Jiménez, and P. M. Krummrich, "Energy- and cost-efficient protection in core networks by a differentiated quality of protection scheme," in *Proc. ECOC, London, UK*, Sep. 2013.

[57] J. Vizcaíno, Y. Ye, F. Jiménez, R. Duque, F. Musumeci, M. Tornatore, P. M. Krummrich, and A. Pattavina, "Quality of protection schemes with extended flexibility for improved energy efficiency in transport networks," in *Proc. DRCN, Budapest, Hungary*, Mar. 2013.

[58] J. López, Y. Ye, V. López, F. Jiménez, R. Duque, F. Musumeci, A. Pattavina, and P. M. Krummrich, "Differentiated quality of protection to improve energy efficiency of survivable optical transport networks," in *Proc. OFC, Anaheim, USA*, Mar. 2013.

[59] J. Mata, Y. Ye, and J. López Vizcaíno, "Embodied and oper-

ational energy optimization for improved energy efficiency in transport networks," in *Proc. ICTON, Graz, Austria*, Sep. 2014.

[60] J. Mata, Y. Ye, J. López Vizcaíno, and I. Monroy, "Influence of embodied energy in the energy efficiency of optical transport networks," in *Proc. ECOC, London, UK*, Sep. 2013.

[61] N. Naas, B. Kantarci, and H. Mouftah, "Multi-granular optical transport network design with dual power state," in *Proc. GLOBECOM Workshop on Management of Emerging Networks and Services, Anaheim, USA*, Dec. 2012.

[62] ——, "Energy-efficient realistic design and planning of optical backbone with multi-granular switching," in *Proc. ICTON, Coventry, UK*, July 2012.

[63] ——, "Power and cost reduction in optical transport networks by multi-granular switching with optical reach consideration," in *Proc. QBSC, Kingston, Canada*, May 2012.

[64] ——, "Design considerations for energy-efficient multi-granular optical networks," in *Proc. HONET, Istanbul, Turkey*, Dec. 2011.

[65] A. Silvestri, A. Valenti, S. Pompei, F. Matera, A. Cianfrani, and A. Coiro, "Energy saving in optical transport networks exploiting transmission properties and wavelength path optimization," *Elsevier OSN*, vol. 7, no. 3, pp. 108–114, July 2010.

[66] A. Silvestri, A. Valenti, S. Pompei, F. Matera, and A. Cianfrani, "Wavelength path optimization in optical transport networks for energy saving," in *Proc. ICTON, Azores, Portugal*, June 2009.

[67] S. Gebert, D. Hock, M. Hartmann, J. Spoerhase, T. Zinner, and P. Tran-Gia, "Including energy efficiency aspects in multi-layer optical network design," in *Proc. ICCE, Danang, Vietnam*, July 2014.

[68] Y. Lui, G. Shen, and S. K. Bose, "Energy-efficient opaque IP over WDM networks with survivability and security constraints," in *Proc. ACP, Beijing, China*, Nov. 2013.

[69] A. Bianco, E. Bonetto, D. Cuda, G. Gavilanes Castillo, M. Mellia, and F. Neri, "Energy-efficient design of wavelength-routing networks," in *Proc. ECOC, Torino, Italy*, Sep. 2010.

[70] A. Ahmad, A. Bianco, E. Bonetto, D. Cuda, G. Gavilanes Castillo, and F. Neri, "Power-aware logical topology design heuristics in wavelength-routing networks," in *Proc. ONDM, Bologna, Italy*, Feb. 2011.

[71] B. Sansò and H. Mellah, "On reliability, performance and internet power consumption," in *Proc. DRCN, Washington, USA*, Oct. 2009.

[72] A. Coiro, M. Listanti, T. Squarcia, A. Valenti, and F. Matera, "Energy-minimised virtual topology design in IP over WDM backbone networks," *IET Optoelectronics, Special Issue on Green Photonics*, vol. 6, no. 4, pp. 165–172, Aug. 2012.

[73] G. Shen, Y. Lui, and S. K. Bose, ""Follow the Sun, Follow the Wind" lightpath virtual topology reconfiguration in IP over WDM network," *IEEE/OSA JLT*, vol. 32, no. 11, pp. 2094–2105, June 2014.

[74] B. Puype, W. Vereecken, D. Colle, M. Pickavet, and P. Demeester, "Multilayer traffic engineering for energy efficiency," *Springer PNET*, vol. 21, no. 2, pp. 127–140, Apr. 2011.

[75] ——, "Power reduction techniques in multilayer traffic engineering," in *Proc. ICTON, Azores, Portugal*, June 2009.

[76] B. Puype, D. Colle, M. Pickavet, and P. Demeester, "Energy efficient multilayer traffic engineering," in *Proc. ECOC, Vienna, Austria*, Sep. 2009.

[77] C. Lee, Y. Kim, and J.-K. K. Rhee, "Green IP-over-WDM network design considering energy-load proportionality," in *Proc. ICNC, Maui, USA*, Jan. 2012.

[78] X. Dong, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Energy efficiency of optical OFDM-based networks," in *Proc. ICC, Budapest, Hungary*, June 2013.

[79] Y. Lui, G. Shen, and W. Shao, "Design for energy-efficient IP over WDM networks with joint lightpath bypass and router-card sleeping strategies," *IEEE/OSA JOCN*, vol. 5, no. 11, pp. 1122–11 138, Nov. 2013.

[80] ——, "Energy-minimized design for IP over WDM networks under modular router line cards," in *Proc. ICCC, Beijing, China*, Aug. 2012.

[81] F. Idzikowski, L. Chiaraviglio, and F. Portoso, "Optimal design of green multi-layer core networks," in *Proc. e-Energy, Madrid, Spain*, May 2012.

[82] A. Ahmad, A. Bianco, E. Bonetto, L. Chiaraviglio, and F. Idzikowski, "Energy-aware design of multilayer core networks," *IEEE/OSA JOCN*, vol. 5, no. 10, pp. A127–A143, Oct. 2013.

[83] F. Musumeci, M. Tornatore, J. López Vizcaíno, Y. Ye, and A. Pattavina, "Energy-efficiency of protected IP-over-WDM networks with sleep-mode devices," *IOS JHSN*, vol. 1, no. 19, pp. 19–32, Mar. 2013.

[84] ——, "Power-aware design of protected IP-over-WDM networks with sleep-mode devices," in *Proc. greencom, online conference*, Sep. 2012.

[85] G. Shen and R. S. Tucker, "Energy-minimized design for IP over WDM networks," *IEEE/OSA JOCN*, vol. 1, no. 1, pp. 176–186, June 2009.

[86] A. Betker, D. Kosiankowski, C. Lange, F. Pfeuffer, C. Raack, and A. Werner, "Energy efficiency in extensive multilayer core and regional networks with protection," Konrad-Zuse-Zentrum für Informationstechnik Berlin, Tech. Rep. ZR 12-45, Dec. 2012.

[87] ——, "Energy efficiency in extensive IP-over-WDM networks with protection," in *Springer Operations Research Proceedings 2012*, ser. Operations Research Proceedings, 2014, pp. 93–99.

[88] P. Chowdhury, M. Tornatore, and B. Mukherjee, "On the energy efficiency of Mixed-Line-Rate networks," in *Proc. OFC, San Diego, USA*, Mar. 2010.

[89] P. Chowdhury, M. Tornatore, A. Nag, E. Ip, T. Wang, and B. Mukherjee, "On the design of energy-efficient Mixed-Line-Rate (MLR) optical networks," *IEEE/OSA JLT*, vol. 30, no. 1, pp. 130–139, Jan. 2012.

[90] A. Bianco, E. Bonetto, F. Musumeci, A. Pattavina, and M. Tornatore, "CapEx/OpEx evaluation of circuit vs packet switched optical networks," in *Proc. ONDM, Brest, France*, Apr. 2013.

[91] L. Wang, R. Lu, Q. Li, X. Zheng, and H. Zhang, "Energy efficient design for multi-shelf IP over WDM networks," in *Proc. INFOCOM Workshop on Green Communications and Networking, Shanghai, China*, Apr. 2011.

[92] X. Dong, T. El-Gorashi, and J. M. H. Elmirghani, "Renewable energy in IP over WDM networks," in *Proc. ICTON, Munich, Germany*, June 2010.

[93] ——, "IP over WDM networks employing renewable energy sources," *IEEE/OSA JLT*, vol. 29, no. 1, pp. 3–14, Jan. 2011.

[94] X. Dong, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Energy efficient optical networks with minimized non-renewable power consumption," *AP JON*, vol. 7, no. 5, pp. 821–831, May 2012.

[95] X. Dong, A. Lawey, T. El-Gorashi, and J. M. H. Elmirghani, "Energy-Efficient Core Networks," in *Proc. ONDM, Colch-

ester, UK, Apr. 2012.

[96] X. Dong, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "On the energy efficiency of physical topology design for IP over WDM networks," *IEEE/OSA JLT*, vol. 30, no. 12, pp. 1931–1942, June 2012.

[97] J. Perelló, A. Morea, S. Spadaro, A. Pages, S. Ricciardi, M. Gunkel, and G. Junyent, "Power consumption reduction through elastic data rate adaptation in survivable multi-layer optical networks," *Springer PNET*, pp. 1–11, June 2014.

[98] G. Rizzelli, A. Morea, M. Tornatore, and O. Rival, "Energy efficient traffic-aware design of on-off multi-layer translucent optical networks," *Elsevier ComNet*, vol. 56, no. 10, pp. 2443–2455, July 2012.

[99] G. Rizzelli, A. Morea, C. Dorize, O. Rival, and M. Tornatore, "On the energy impact of transmission reach for 100g IP-over-WDM translucent optical networks," in *Proc. ECOC, Amsterdam, The Netherlands*, Sep. 2012.

[100] G. Rizzelli, A. Morea, and M. Tornatore, "An analysis of daily power consumption under different on-off IP-over-WDM translucent design approaches," in *Proc. OFC, Anaheim, USA*, Mar. 2013.

[101] A. Morea, G. Rizzelli, and M. Tornatore, "On the energy and cost trade-off of different energy-aware network design strategies," in *Proc. OFC, Anaheim, USA*, Mar. 2013.

[102] G. Rizzelli, A. Morea, M. Tornatore, and A. Pattavina, "Reach-related energy consumption in IP-over-WDM 100G translucent networks," *IEEE/OSA JLT*, vol. 31, no. 11, pp. 1828–1834, June 2013.

[103] W. Shen, Y. Tsukishima, K. Yamada, and M. Jinno, "Power-efficient multi-layer traffic networking: Design and evaluation," in *Proc. ONDM, Kyoto, Japan*, Feb. 2010.

[104] F. Musumeci, M. Tornatore, and A. Pattavina, "A power consumption analysis for IP-over-WDM core network architectures," *IEEE/OSA JOCN*, vol. 4, no. 2, pp. 108–117, Feb. 2012.

[105] F. Musumeci, M. Tornatore, G. Fontana, M. Riunno, S. Bregni, and A. Pattavina, "Energy-efficiency of all-optical transport through time-driven switching," *IET Optoelectronics, Special Issue on Green Photonics*, vol. 6, no. 4, pp. 173–182, Aug. 2012.

[106] F. Musumeci, F. Vismara, V. Grkovic, M. Tornatore, and A. Pattavina, "On the energy efficiency of optical transport with time driven switching," in *Proc. ICC, Kyoto, Japan*, June 2011.

[107] E. Yetginer and G. N. Rouskas, "Power efficient traffic grooming in optical WDM networks," in *Proc. GLOBECOM, Honolulu, USA*, Dec. 2009.

[108] A. Fallahpour, H. Beyranvand, S. A. Nezamalhosseini, and J. A. Salehi, "Energy efficient routing and spectrum assignment with regenerator placement in elastic optical networks," *IEEE/OSA JLT*, vol. 32, no. 10, pp. 2019–2027, May 2014.

[109] A. Ahmad, A. Bianco, and E. Bonetto, "Traffic grooming and energy-efficiency in flexible-grid networks," in *Proc. ICC, Sydney, Australia*, June 2014.

[110] E. Palkopoulou, D. A. Schupke, and T. Bauschert, "Energy efficiency and CAPEX minimization for backbone network planning: Is there a tradeoff?" in *Proc. ANTS, New Delhi, India*, Dec. 2009.

[111] A. Klekamp, U. Gebhard, and F. Ilchmann, "Efficiency of adaptive and Mixed-Line-Rate IP over DWDM networks regarding CAPEX and power consumption [invited]," *IEEE/OSA JOCN*, vol. 4, no. 11, pp. B11–B16, Nov. 2012.

[112] ——, "Efficiency of adaptive and Mixed-Line-Rate IP over DWDM networks regarding CAPEX and power consumption," in *Proc. OFC, Los Angeles, USA*, Mar. 2012.

[113] ——, "Energy and cost efficiency of adaptive and Mixed-Line-Rate IP over DWDM networks," *IEEE/OSA JLT*, vol. 30, no. 2, pp. 215–221, Jan. 2012.

[114] G. Eilenberger, S. Bunse, L. Dembeck, U. Gebhard, F. Ilchmann, W. Lautenschlaeger, and J. Milbrandt, "Energy-efficient transport for the future internet," *Bell Labs Technical Journal*, vol. 15, no. 2, pp. 147–168, Sep. 2010.

[115] A. Bianco, E. Bonetto, and A. Ahmad, "Energy awareness in the design of optical core networks," in *Proc. OFC, Anaheim, USA*, Mar. 2013.

[116] F. Musumeci, M. Tornatore, R. Fiandra, and A. Pattavina, "The role of network topology on the energy efficiency of IP-over-WDM architectures," in *Proc. ONDM, Colchester, UK*, Apr. 2012.

[117] F. Vismara, V. Grkovic, F. Musumeci, M. Tornatore, and S. Bregni, "On the energy efficiency of IP-over-WDM networks," in *Proc. LATINCOM, Bogota, Colombia*, Sep. 2010.

[118] X. Dong, T. El-Gorashi, and J. M. H. Elmirghani, "Hybrid-power IP over WDM network," in *Proc. WOCN, Colombo, Sri Lanka*, Sep. 2010.

[119] W. Hou, L. Guo, and X. Gong, "Survivable power efficiency oriented integrated grooming in green networks," *Journal of Network and Computer Applications*, vol. 36, no. 1, pp. 420–428, Jan. 2013.

[120] W. Hou, L. Guo, X. Wei, and X. Gong, "Multi-granularity and robust grooming in power- and port-cost-efficient IP over WDM networks," *Elsevier ComNet*, vol. 56, no. 10, pp. 2383–2399, July 2012.

[121] C. Lee and J.-K. K. Rhee, "Traffic grooming for IP-over-WDM networks: Energy and delay perspectives," *IEEE/OSA JOCN*, vol. 6, no. 2, pp. 96–103, Feb. 2014.

[122] X. Zhang, H. Wang, and Z. Zhang, "Survivable green IP over WDM networks against double-link failures," *Elsevier ComNet*, vol. 59, no. 0, pp. 62–76, Feb. 2014.

[123] F. Idzikowski, E. Bonetto, L. Chiaraviglio, A. Cianfrani, A. Coiro, R. Duque, F. Jiménez, E. Le Rouzic, F. Musumeci, W. Van Heddeghem, J. López Vizcaíno, and Y. Ye, "TREND in Energy-Aware Adaptive Routing Solutions," *IEEE ComMag*, vol. 51, no. 11, pp. 94–104, Nov. 2013.

[124] F. Idzikowski *et al.*, "Final report for the IRA "Energy-efficient use of network core resources"," TREND Project, Deliverable D3.3, 2012.

[125] Ç. Çavdar, M. Ruiz, P. Monti, L. Velasco, and L. Wosinska, "Design of green optical networks with signal quality guarantee," in *Proc. ICC, Ottawa, Canada*, June 2012.

[126] Ç. Çavdar, A. Yayimli, and L. Wosinska, "How to cut the electric bill by routing and wavelength assignment with time-zones and time-of-use prices," in *Proc. ACP, Shanghai, China*, Nov. 2011.

[127] ——, "How to cut the electric bill in optical WDM networks with time-zones and time-of-use prices," in *Proc. ECOC, Geneva, Switzerland*, Sep. 2011.

[128] A. Coiro, M. Listanti, and A. Valenti, "Impact of energy-aware topology design and adaptive routing at different layers in IP over WDM networks," in *Proc. Networks, Rome Italy*, Oct. 2012.

[129] A. Coiro, M. Listanti, A. Valenti, and F. Matera, "Reducing power consumption in wavelength routed networks by selective switch off of optical links," *IEEE JSTQE*, vol. 17, no. 2, pp. 428–436, Mar./Apr. 2011.

[130] J. Perelló, A. Morea, S. Spadaro, and M. Tornatore, "Link vs. opto-electronic device sleep mode approaches in survivable green optical networks," in *Proc. OFC, Anaheim, USA*, Mar.

2013.

[131] A. Morea, J. Perelló, and S. Spadaro, “Traffic variation-aware networking for energy efficient optical communications,” in *Proc. ONDM, Brest, France*, Apr. 2013.

[132] A. Morea, J. Perelló, S. Spadaro, D. Verchère, and M. Vigoureux, “Protocol enhancements for ’greening’ optical networks,” *Bell Labs Technical Journal*, vol. 18, no. 3, pp. 211–230, Dec. 2013.

[133] I. Cerutti, N. Sambo, and P. Castoldi, “Sleeping link selection for energy-efficient GMPLS networks,” *IEEE/OSA JLT*, vol. 29, no. 15, pp. 2292–2298, Aug. 2011.

[134] W. Hou, L. Guo, X. Wang, and X. Wei, “Joint port-cost and power-consumption savings in hybrid hierarchical optical networks,” *Elsevier OSN, Special Issue on Green Communications*, vol. 8, no. 3, pp. 214–224, July 2011.

[135] A. Coiro, M. Listanti, A. Valenti, and F. Matera, “Power-aware routing and wavelength assignment in multi-fiber optical networks,” *IEEE/OSA JOCN*, vol. 3, no. 11, pp. 816–829, Nov. 2011.

[136] P. Monti, A. Muhammad, Ç. Çavdar, I. Cerutti, L. Wosinska, P. Castoldi, and A. Tzanakaki, “Energy-efficient lightpath provisioning in a static WDM network with dedicated path protection,” in *Proc. ICTON, Stockholm, Sweden*, June 2011.

[137] A. Jirattigalachote, Ç. Çavdar, P. Monti, L. Wosinska, and A. Tzanakaki, “Dynamic provisioning strategies for energy efficient WDM networks with dedicated path protection,” *Elsevier OSN, Special Issue on Green Communications*, vol. 8, no. 3, pp. 171–180, July 2011.

[138] P. Wiatr, P. Monti, and L. Wosinska, “Power savings versus network performance in dynamically provisioned WDM networks,” *IEEE ComMag*, vol. 50, no. 5, pp. 48–55, May 2012.

[139] A. Muhammad, P. Monti, I. Cerutti, L. Wosinska, and P. Castoldi, “Reliability differentiation in energy efficient optical networks with shared path protection,” in *Proc. OnlineGreenComm, online conference*, Oct. 2013.

[140] D. Tafani, B. Kantarci, H. Mouftah, C. McArdle, and L. Barry, “Distributed management of energy-efficient lightpaths for computational grids,” in *Proc. GLOBECOM, Anaheim, USA*, Dec. 2012.

[141] ——, “Energy-efficient lightpaths for computational grids,” in *Proc. ICTON, Coventry, UK*, July 2012.

[142] N.-H. Bao, L.-M. Li, H.-F. Yu, Z.-Z. Zhang, and H.-B. Luo, “Power-aware provisioning strategy with shared path protection in optical WDM networks,” *Elsevier OFT*, vol. 18, no. 2, pp. 81–87, Mar. 2011.

[143] J. López Vizcaíno, Y. Ye, and I. Tafur Monroy, “Energy efficiency analysis for dynamic routing in optical transport networks,” in *Proc. ICC, Ottawa, Canada*, June 2012.

[144] J. López Vizcaíno, Y. Ye, V. López, F. Jiménez, R. Duque, P. M. Krummrich, F. Musumeci, M. Tornatore, and A. Pattavina, “Traffic and power-aware protection scheme in elastic optical networks,” in *Proc. Networks, Rome Italy*, Oct. 2012.

[145] J. López Vizcaíno, P. Soto, Y. Ye, F. Jiménez, and P. M. Krummrich, “Energy-efficient and low blocking probability differentiated quality of protection scheme for dynamic elastic optical networks,” in *Proc. SoftCOM, Primosten, Croatia*, Sep. 2013.

[146] A. Coiro, A. Valenti, F. Matera, and M. Settembre, “Reducing power consumption in core wavelength division multiplexing optical networks,” *Taylor & Francis FIO*, vol. 30, no. 3, pp. 166–177, June 2011.

[147] S. Ricciardi, F. Palmieri, U. Fiore, D. Careglio, G. Santos-Boada, and J. Solé-Pareta, “An energy-aware dynamic RWA framework for next-generation wavelength-routed networks,” *Elsevier ComNet*, vol. 56, no. 10, pp. 2420–2442, July 2012.

[148] A. Morea, O. Rival, N. Brochier, and E. Le Rouzic, “Datarate adaptation for night-time energy savings in core networks,” *IEEE/OSA JLT*, vol. 31, no. 5, pp. 779–785, Mar. 2013.

[149] I. Cerutti, N. Sambo, and P. Castoldi, “Distributed support of link sleep mode for energy efficient GMPLS networks,” in *Proc. ECOC, Torino, Italy*, Sep. 2010.

[150] A. Leiva, J. Fiochietto, V. López, B. Huiszoon, and A. Beghelli, “Comparison of static and dynamic WDM networks in terms of energy consumption,” in *Proc. OFC, San Diego, USA*, Mar. 2010.

[151] A. Leiva, J. Fiochietto, B. Huiszoon, V. López, M. Tarifeño, J. Aracil, and A. Beghelli, “Comparison in power consumption of static and dynamic WDM networks,” *Elsevier OSN, Special Issue on Green Communications*, vol. 8, no. 3, pp. 149–161, July 2011.

[152] F. Farahmand, I. Cerutti, M. M. Hasan, and J. P. Jue, “Energy-efficiency of drop-and-continue traffic grooming,” in *Proc. OFC, Los Angeles, USA*, Mar. 2011.

[153] M. M. Hasan, F. Farahmand, J. P. Jue, and Z. Zhu, “Knapsack-based drop-and-continue traffic grooming for power and resource efficiency,” in *Proc. OFC, Los Angeles, USA*, Mar. 2012.

[154] S. Zhang and B. Mukherjee, “Energy-efficient dynamic provisioning for spectrum elastic optical networks,” in *Proc. ICC, Ottawa, Canada*, June 2012.

[155] A. Coiro, M. Listanti, and A. Valenti, “Dynamic power-aware routing and wavelength assignment for green WDM optical networks,” in *Proc. ICC, Kyoto, Japan*, June 2011.

[156] P. Jaskóła, P. Arabas, and A. Karbowski, “Combined calculation of optimal routing and bandwidth allocation in energy aware networks,” in *Proc. ITC, Karlskrona, Sweden*, Sep. 2014.

[157] E. Niewiadomska-Szynkiewicz, A. Sikora, P. Arabas, and J. Kołodziej, “Control system for reducing energy consumption in backbone computer network,” *Concurrency and Computation: Practice and Experience (Wiley), Special Issue*, vol. 25, no. 12, pp. 1738–1754, Aug. 2013.

[158] M. Caria, M. Chamania, and A. Jukan, “To switch on or off: A simple case study on energy efficiency in IP-over-WDM networks,” in *Proc. HPSR, Cartagena, Spain*, July 2011.

[159] ——, “Trading IP routing stability for energy efficiency: A case for traffic offloading with optical bypass,” in *Proc. ONDM, Bologna, Italy*, Feb. 2011.

[160] ——, “A Comparative Performance Study of Load Adaptive Energy Saving Schemes for IP-Over-WDM Networks,” *IEEE/OSA JOCN*, vol. 4, no. 3, pp. 152–164, Mar. 2012.

[161] M. Zhang, C. Yi, B. Liu, and B. Zhang, “GreenTE: Power-aware traffic engineering,” in *Proc. ICNP, Kyoto, Japan*, Oct. 2010.

[162] B. Addis, A. Capone, G. Carello, L. Gianoli, and B. Sansò, “Energy management through optimized routing and device powering for greener communication networks,” *IEEE/ACM ToN*, vol. 22, no. 1, pp. 313–325, Feb. 2014.

[163] ——, “A robust optimization approach for energy-aware routing in MPLS networks,” in *Proc. ICNC, San Diego, USA*, Jan. 2013.

[164] ——, “Energy-aware multiperiod traffic engineering with flow-based routing,” in *Proc. ICC Workshop on Green Communications and Networking, Ottawa, Canada*, June 2012.

[165] F. Giroire, J. Moulierac, T. K. Phan, and F. Roudaut, “Minimization of network power consumption with redundancy elimination,” in *Proc. Networking, Prague, Czech Republic*,

May 2012.
[166] D. Coudert, A. M. C. A. Koster, T. K. Phan, and M. Tieevs, "Robust redundancy elimination for energy-aware routing," in *Proc. GreenCom, Beijing, China*, Aug. 2013.
[167] D. Coudert, A. Kodjo, and T. K. Phan, "Robust energy-aware routing with redundancy elimination," Institut National de Recherche en Informatique et en Automatique (INRIA), Tech. Rep. 8457, Jan. 2014.
[168] A. M. C. A. Koster, T. K. Phan, and M. Tieevs, "Extended cutset inequalities for the network power consumption problem," in *Proc. INOC, Tenerife, Spain*, May 2013.
[169] E. Amaldi, A. Capone, and L. G. Gianoli, "Energy-aware IP traffic engineering with shortest path routing," *Elsevier ComNet*, vol. 57, no. 6, pp. 1503–1517, Apr. 2013.
[170] A. Capone, C. Cascone, L. Gianoli, and B. Sansò, "OSPF optimization via dynamic network management for green IP networks," in *Proc. SustainIT, Palermo, Italy*, Oct. 2013.
[171] B. Addis, A. Capone, G. Carello, L. Gianoli, and B. Sansò, "Multi-period traffic engineering of resilient networks for energy efficiency," in *Proc. greencom, online conference*, Sep. 2012.
[172] ——, "Energy aware management of resilient networks with shared protection," in *Proc. SustainIT, Pisa, Italy*, Oct. 2012.
[173] C.-C. Cheung, H.-W. Chu, and S. S. Xu, "A new optimization algorithm for power saving in backbone networks," in *Proc. ICCCN, Shanghai, China*, Aug. 2014.
[174] R. Wang, Z. Jiang, S. Gao, W. Yang, Y. Xia, and M. Zhu, "Energy-aware routing algorithms in Software-Defined Networks," in *Proc of the WoWMom, Sydney, Australia*, June 2014.
[175] B. Addis, A. Capone, G. Carello, L. Gianoli, and B. Sansò, "On the energy cost of robustness and resiliency in IP networks," *Elsevier ComNet*, vol. 75, Part A, no. 0, pp. 239–259, Dec. 2014.
[176] A. A. Kist and A. Aldraho, "Dynamic topologies for sustainable and energy efficient traffic routing," *Elsevier ComNet*, vol. 55, no. 9, pp. 2271–2288, June 2011.
[177] A. Aldraho and A. A. Kist, "Enabling energy efficient and resilient networks using dynamic topologies," in *Proc. SustainIT, Pisa, Italy*, Oct. 2012.
[178] R. G. Garroppo, S. Giordano, G. Nencioni, M. Pagano, and M. G. Scutellá, "Energy saving heuristics in backbone networks," in *Proc. SustainIT, Pisa, Italy*, Oct. 2012.
[179] L. Chiaraviglio, M. Mellia, and F. Neri, "Reducing power consumption in backbone networks," in *Proc. ICC, Dresden, Germany*, June 2009.
[180] ——, "Minimizing ISP network energy cost: Formulation and solutions," *IEEE/ACM ToN*, vol. 20, no. 2, pp. 463–476, Apr. 2012.
[181] A. P. Bianzino, C. Chaudet, F. Larroca, D. Rossi, and J.-L. Rougier, "Energy-Aware Routing: a Reality Check," in *Proc. GLOBECOM Workshops, Miami, USA*, Dec. 2010.
[182] Y.-M. Kim, E.-J. Lee, H.-S. Park, J.-K. Choi, and H.-S. Park, "Ant colony based self-adaptive energy saving routing for energy efficient Internet," *Elsevier ComNet*, vol. 56, no. 10, pp. 2343–2354, July 2012.
[183] F. Francois, N. Wang, K. Moessner, S. Georgoulas, and R. d. O. Schmidt, "Leveraging MPLS backup paths for distributed energy-aware traffic engineering," *IEEE TNSM*, vol. 11, no. 2, pp. 235–249, June 2014.
[184] F. Francois, N. Wang, K. Moessner, S. Georgoulas, and K. Xu, "Green IGP link weights for energy-efficiency and load-balancing in IP backbone networks," in *Proc. IFIP Networking, New York, USA*, May 2013.
[185] ——, "On IGP link weight optimization for joint energy efficiency and load balancing improvement," *Elsevier ComCom*, vol. 50, no. 0, pp. 130–141, Sep. 2014.
[186] L. Chiaraviglio, A. Cianfrani, E. Le Rouzic, and M. Polverini, "Sleep modes effectiveness in backbone networks with limited configurations," *Elsevier ComNet*, vol. 57, no. 15, pp. 2931–2948, Oct. 2013.
[187] B. Zhou, L. Wang, F. Zhang, X. Jin, and Z. Liu, "DEER: a distributed routing scheme for achieving network energy efficiency," in *Proc. LANMAN, Reno, USA*, May 2014.
[188] S. S. W. Lee, P.-K. Tseng, and A. Chen, "Link weight assignment and loop-free routing table update for link state routing protocols in energy-aware internet," *Elsevier FGCS*, vol. 28, no. 2, pp. 437–445, Feb. 2012.
[189] A. P. Bianzino, L. Chiaraviglio, and M. Mellia, "Distributed algorithms for green IP networks," in *Proc. INFOCOM workshop on Communications and Control for Sustainable Energy Systems, Orlando, USA*, Mar. 2012.
[190] Y. Lui, G. Shen, and W. Shao, "Optimal port grouping for maximal router card sleeping," in *Proc. ACP, Guangzhou, China*, Nov. 2012.
[191] A. Coiro, L. Chiaraviglio, A. Cianfrani, M. Listanti, and M. Polverini, "Reducing power consumption in IP networks through table lookup bypass," *Elsevier ComNet*, vol. 64, no. 0, pp. 125–142, May 2014.
[192] A. Coiro, M. Polverini, A. Cianfrani, and M. Listanti, "Energy saving improvements in IP networks through table lookup bypass in router line cards," in *Proc. ICNC, San Diego, USA*, Jan. 2013.
[193] F. Idzikowski, S. Orlowski, C. Raack, H. Woesner, and A. Wolisz, "Saving energy in IP-over-WDM networks by switching off line cards in low-demand scenarios," in *Proc. ONDM, Kyoto, Japan*, Feb. 2010.
[194] ——, "Dynamic routing at different layers in IP-over-WDM networks – maximizing energy savings," *Elsevier OSN, Special Issue on Green Communications*, vol. 8, no. 3, pp. 181–200, July 2011.
[195] E. Bonetto, L. Chiaraviglio, F. Idzikowski, and E. Le Rouzic, "Algorithms for the multi-period power-aware logical topology design with reconfiguration costs," *IEEE/OSA JOCN*, vol. 5, no. 5, pp. 394–410, May 2013.
[196] F. Feller, "Evaluation of centralized solution methods for the dynamic optical bypassing problem," in *Proc. ONDM, Brest, France*, Apr. 2013.
[197] F. Giroire, D. Mazauric, J. Moulierac, and B. Onfroy, "Minimizing routing energy consumption: from theoretical to practical results," in *Proc. GreenCom, Hangzhou, China*, Dec. 2010.
[198] ——, "Minimizing routing energy consumption: from theoretical to practical results," Institut National de Recherche en Informatique et en Automatique (INRIA), Tech. Rep. 7234, July 2010.
[199] F. Giroire, D. Mazauric, and J. Moulierac, *Energy Efficient Routing by Switching-Off Network Interfaces*. IGI Global, 2012, ch. 10, pp. 207–236.
[200] F. Giroire, J. Moulierac, and T. K. Phan, "Optimizing rule placement in software-defined networks for energy-aware routing," in *Proc. GLOBECOM, Austin, USA*, Dec. 2014.
[201] ——, "Optimizing rule placement in software-defined networks for energy-aware routing," Institut National de Recherche en Informatique et en Automatique (INRIA), Tech. Rep. 8537, May 2014.
[202] F. Francois, N. Wang, K. Moessner, and S. Georgoulas, "Optimizing link sleeping reconfigurations in ISP networks

with off-peak time failure protection," *IEEE TNSM*, vol. 10, no. 2, pp. 176–188, June 2013.

[203] J. Moulierac and T. K. Phan, "Optimizing IGP link weights for energy-efficiency in a changing world," Institut National de Recherche en Informatique et en Automatique (INRIA), Tech. Rep. 8534, May 2014.

[204] E. Ghazisaeedi, N. Wang, and R. Tafazolli, "Link sleeping optimization for green virtual network infrastructures," in *Proc. Globecom Workshops, Anaheim, USA*, Dec. 2012.

[205] S. S. W. Lee, P.-K. Tseng, and A. Chen, "A distributed link management algorithm for energy efficient IP networks," in *Proc. GLOBECOM, Houston, USA*, Dec. 2011.

[206] S. S. W. Lee, K.-Y. Li, and A. Chen, "Energy efficient multi-topology routing configurations for fast failure reroute in IP networks," in *Proc. GLOBECOM, Anaheim, USA*, Dec. 2012.

[207] G. Lin, S. Soh, and K.-W. Chin, "Energy-aware traffic engineering with reliability constraint," *Elsevier ComCom*, vol. 57, no. 0, pp. 115–128, Feb. 2015.

[208] M. Shen, H. Liu, K. Xu, N. Wang, and Y. Zhong, "Routing on demand: toward the energy-aware traffic engineering with OSPF," in *Proc. IFIP Networking, Prague, Czech Republic*, May 2012.

[209] P. Lai, Q. Yang, C. Wu, and M. Jiang, "Configuring network topology towards energy-efficient IP networks," in *Proc. ICCSN, Xi'an, China*, May 2011.

[210] E. Amaldi, A. Capone, S. Coniglio, and L. G. Gianoli, "Energy-aware traffic engineering with elastic demands and MMF bandwidth allocation," in *Proc of the CAMAD, Berlin, Germany*, Sep. 2013.

[211] L. Chiaraviglio, P. Wiatr, P. Monti, J. Chen, J. Lorincz, F. Idzikowski, M. Listanti, and L. Wosinska, "Is green networking beneficial in terms of device lifetime?" *IEEE ComMag*, vol. 53, no. 5, pp. 232–240, May 2015.

[212] K.-H. Ho and C.-C. Cheung, "Green distributed routing protocol for sleep coordination in wired core networks," in *Proc. INC, Gyeongju, South Korea*, May 2010.

[213] "ECONET – low Energy COsonsumption NETworks," http://www.econet-project.eu/, 2010–2013.

[214] D. Reforgiato, A. Lombardo, F. Davoli, L. Fialho, M. Collier, P. Donadio, R. Bolla, and R. Bruschi, "Exporting data-plane energy-aware capabilities from network devices toward the control plane: The Green Abstraction Layer," in *Proc. NOC, Vilanova i la Geltru, Spain*, June 2012.

[215] S. Avallone and G. Ventre, "Energy efficient online routing of flows with additive constraints," *Elsevier ComNet*, vol. 56, no. 10, pp. 2368–2382, July 2012.

[216] J. Scharf, "Efficiency analysis of distributed dynamic optical bypassing heuristics," in *Proc. ICC Workshop on Green Communications and Networking, Ottawa, Canada*, June 2012.

[217] F. Idzikowski, R. Duque, F. Jiménez, E. Le Rouzic, L. Chiaraviglio, and M. Ajmone Marsan, "Energy saving in optical operator networks: the challenges, the trend vision, and some results," in *Proc. ECOC, Amsterdam, The Netherlands*, Sep. 2012.

[218] F. Idzikowski, L. Chiaraviglio, R. Duque, F. Jiménez, and E. Le Rouzic, "Green horizon: Looking at backbone networks in 2020 from the perspective of network operators," in *Proc. ICC, Budapest, Hungary*, June 2013.

[219] A. Aldraho and A. A. Kist, "Heuristics for dynamic topologies to reduce power consumption of networks," in *Proc. ATNAC, Auckland, New Zealand*, Oct. 2010.

[220] A. P. Bianzino, C. Chaudet, D. Rossi, J.-L. Rougier, and S. Moretti, "The green-game: Striking a balance between QoS and energy saving," in *Proc. ITC, San Francisco, USA*, Sep. 2011.

[221] A. Cianfrani, V. Eramo, M. Listanti, and M. Polverini, "Introducing routing standby in network nodes to improve energy savings techniques," in *Proc. e-Energy, Madrid, Spain*, May 2012.

[222] L. Chiaraviglio, M. Mellia, and F. Neri, "Energy-aware backbone networks: a case study," in *Proc of the ICC workshop on Green Communications, Dresden, Germany*, June 2009.

[223] E. Bonetto, L. Chiaraviglio, D. Cuda, F. Idzikowski, and F. Neri, "Exploiting traffic dynamics in power-aware logical topology design," in *Proc. ECOC, Geneva, Switzerland*, Sep. 2011.

[224] D. Coudert, A. Kodojo, and T. K. Phan, "Robust optimization for energy-aware routing with redundancy elimination," in *Proc. ALGOTEL, Le-Bois-Plage-en-Ré, France*, June 2014.

[225] B. Mumey, J. Tang, and S. Hashimoto, "Enabling green networking with a power down approach," in *Proc. ICC, Ottawa, Canada*, June 2012.

[226] R. Bolla, R. Bruschi, A. Cianfrani, and M. Listanti, "Introducing standby capabilities into next-generation network devices," in *Proc. PRESTO, Philadelphia, USA*, May 2010.

[227] R. Bolla, R. Bruschi, A. Cianfrani, O. Jaramillo, and M. Listanti, "Energy-efficient sleeping modes for next-generation core networks," in *Proc. FNMS, Warsaw, Poland*, June 2011.

[228] R. Bolla, R. Bruschi, A. Cianfrani, and M. Listanti, "Enabling backbone networks to sleep," *IEEE Network*, vol. 25, no. 2, pp. 26–31, Mar./Apr. 2011.

[229] L. Liu and B. Ramamurthy, "Rightsizing bundle link capacities for energy savings in the core network," in *Proc. GLOBECOM, Houston, USA*, Dec. 2011.

[230] ——, "A dynamic local method for bandwidth adaptation in bundle links to conserve energy in core networks," in *Proc. ANTS, Bangalore, India*, Dec. 2011.

[231] ——, "Investigation of energy savings in optical networks using bundle link rightsizing methods," in *Proc. OFC, Anaheim, USA*, Mar. 2013.

[232] ——, "A dynamic local method for bandwidth adaptation in bundle links to conserve energy in core networks," *Elsevier OSN*, vol. 10, no. 4, pp. 481–490, Nov. 2013.

[233] A. Coiro, F. Iervini, and M. Listanti, "Distributed and adaptive interface switch off for internet energy saving," in *Proc. ICCCN, New Delhi, India*, Aug. 2011.

[234] A. Coiro, M. Listanti, A. Valenti, and F. Matera, "Energy-aware traffic engineering: A routing-based distributed solution for connection-oriented IP networks," *Elsevier ComNet*, vol. 57, no. 9, pp. 2004–2020, June 2013.

[235] A. P. Bianzino, C. Chaudet, S. Moretti, J.-L. Rougier, L. Chiaraviglio, and E. Le Rouzic, "Enabling sleep mode in backbone IP-networks: a criticality-driven tradeoff," in *Proc. ICC Workshop on Green Communications and Networking, Ottawa, Canada*, June 2012.

[236] F. Idzikowski, E. Bonetto, and L. Chiaraviglio, "EWA – an adaptive algorithm using watermarks for energy saving in IP-over-WDM networks," Technische Universität Berlin, Telecommunication Networks Group, Tech. Rep. TKN-12-002, May 2012.

[237] F. Idzikowski, L. Chiaraviglio, and E. Bonetto, "EWA: an adaptive algorithm for energy saving in IP-over-WDM networks," in *Proc. NOC, Vilanova i la Geltru, Spain*, June 2012.

[238] N. Yamanaka, S. Shimizu, and G. Shan, "Energy efficient

network design tool for green IP/Ethernet networks," in *Proc. ONDM, Kyoto, Japan*, Feb. 2010.

[239] H. Takeshita, N. Yamanaka, S. Okamoto, S. Shimizu, and G. Shan, "Energy efficient network design tool for green IP/Ethernet networks," *Elsevier OSN, Special Issue ONDM 2010*, vol. 9, no. 3, pp. 164–270, July 2012.

[240] F. Feller, "An optimization-heuristic approach to dynamic optical bypassing," in *Proc. ITG Fachtagung Photonische Netze, Leipzig, Germany*, May 2012.

[241] ——, "Evaluation of centralized method for one-step multi-layer network reconfiguration," in *Proc. TIWDC, Genoa, Italy*, Sep. 2013.

[242] F. Cuomo, A. Abbagnale, A. Cianfrani, and M. Polverini, "Keeping the connectivity and saving the energy in the Internet," in *Proc. INFOCOM Workshops, Shanghai, China*, Apr. 2011.

[243] F. Cuomo, A. Abbagnale, and S. Papagna, "ESOL: Energy saving in the Internet based on occurrence of links in routing paths," in *Proc. WoWMoM, Lucca, Italy*, June 2011.

[244] Y. Souda, T. Mikoshi, and T. Takenaka, "High-speed topology construction method for network power saving," in *Proc. APCC, Jeju Island, South Korea*, Oct. 2012.

[245] A. P. Bianzino, L. Chiaraviglio, and M. Mellia, "GRiDA: a green distributed algorithm for backbone networks," in *Proc. GreenCom, online*, Sep. 2011.

[246] A. P. Bianzino, L. Chiaraviglio, M. Mellia, and J.-L. Rougier, "GRiDA: GReen Distributed Algorithm for energy-efficient IP backbone networks," *Elsevier ComNet*, vol. 56, no. 14, pp. 3219–3232, Sep. 2012.

[247] A. Cianfrani, V. Eramo, M. Listanti, M. Marazza, and E. Vittorini, "An energy saving routing algorithm for a green OSPF protocol," in *Proc. INFOCOM Workshops, San Diego, USA*, Mar. 2010.

[248] A. Cianfrani, V. Eramo, M. Listanti, and M. Polverini, "An OSPF enhancement for energy saving in IP networks," in *Proc. INFOCOM Workshops, Shanghai, China*, Apr. 2011.

[249] A. Cianfrani, V. Eramo, M. Listanti, M. Listanti, and A. V. Vasilakos, "An OSPF-integrated routing strategy for QoS-aware energy saving in IP backbone networks," *IEEE TNSM*, vol. 9, no. 3, pp. 254–267, Sep. 2012.

[250] F. Cuomo, A. Cianfrani, M. Polverini, and D. Mangione, "Network pruning for energy saving in the Internet," *Elsevier ComNet*, vol. 56, no. 10, pp. 2355–2367, July 2012.

[251] Y. Yang, D. Wang, M. Xu, and S. Li, "Hop-by-hop computing for green internet routing," in *Proc. ICNP, Göttingen, Germany*, Oct. 2013.

[252] L. Chiaraviglio and A. Cianfrani, "On the effectiveness of sleep modes in backbone networks with limited configurations," in *Proc. SoftCOM, Split, Croatia*, Sep. 2012.

[253] L. Chiaraviglio, A. Cianfrani, M. Listanti, L. Mignano, and M. Polverini, "Implementing energy-aware algorithms in backbone networks: a transient analysis," in *Proc. ICC, London, UK*, June 2015.

[254] H. Yonezu, G. Shan, S. Shimizu, D. Ishii, S. Okamoto, E. Oki, and N. Yamanaka, "Network power saving topology calculation method by power ing off links considering QoS," in *Proc. OECC, Sapporo, Japan*, July 2010.

[255] H. Yonezu, K. Kikuta, D. Ishii, S. Okamoto, E. Oki, and N. Yamanaka, "QoS aware energy optimal network topology design and dynamic link power management," in *Proc. ECOC, Torino, Italy*, Sep. 2010.

[256] Y. Song and M. Liu, "Greedy-based distributed algorithms for green traffic routing," in *Proc. ICCCN, Shanghai, China*, Aug. 2014.

[257] M. Kamola and P. Arabas, "Shortest path green routing and the importance of traffic matrix knowledge," in *Proc. TIWDC, Genoa, Italy*, Sep. 2013.

[258] Y. Yang, M. Xu, and Q. Li, "Towards fast rerouting-based energy efficient routing," *Elsevier ComNet*, vol. 70, no. 0, pp. 1–15, Sep. 2014.

[259] Y.-M. Kim, E.-J. Lee, and H.-S. Park, "Ant colony optimization based energy saving routing for energy-efficient networks," *IEEE Communications Letters*, vol. 15, no. 7, pp. 779–781, July 2011.

[260] M. Charalambides, D. Tuncer, L. Mamatas, and G. Pavlou, "Energy-aware adaptive network resource management," in *Proc. IM, Ghent, Belgium*, May 2013.

[261] G. Wu and G. Mohan, "Power-efficient integrated routing of sublambda connection requests with traffic splitting in IP over WDM networks," *Elsevier ComNet*, vol. 70, no. 0, pp. 16–29, Sep. 2014.

[262] Y. Zhang, M. Tornatore, P. Chowdhury, and B. Mukherjee, "Energy optimization in IP-over-WDM networks," *Elsevier OSN, Special Issue on Green Communications*, vol. 8, no. 3, pp. 171–180, July 2011.

[263] Y. Chen and A. Jaekel, "Energy efficient grooming of scheduled sub-wavelength traffic demands," in *Proc. OFC, Los Angeles, USA*, Mar. 2011.

[264] ——, "Energy-aware scheduling and resource allocation for periodic traffic demands," *IEEE/OSA JOCN*, vol. 5, no. 4, pp. 261–270, Apr. 2013.

[265] Y. Zhang, M. Tornatore, P. Chowdhury, and B. Mukherjee, "Time-aware energy conservation in IP-over-WDM networks," in *Proc. PS, Monterey, USA*, July 2010.

[266] S. Zhang, D. Shen, and C.-K. Chan, "Energy-efficient traffic grooming in WDM networks with scheduled time traffic," *IEEE/OSA JLT*, vol. 29, no. 17, pp. 2577–2584, Sep. 2011.

[267] S. Zhang, D. Shen, and C. Chan, "Energy efficient time-aware traffic grooming in wavelength routing networks," in *Proc. GLOBECOM, Miami, USA*, Dec. 2010.

[268] F. Farahmand, M. M. Hasan, I. Cerutti, J. P. Jue, and J. J. P. C. Rodrigues, "Differentiated energy savings in optical networks with grooming capabilities," in *Proc. GLOBECOM, Miami, USA*, Dec. 2010.

[269] M. M. Hasan, F. Farahmand, A. N. Patel, and J. P. Jue, "Traffic grooming in green optical networks," in *Proc. ICC, Cape Town, South Africa*, May 2010.

[270] M. M. Hasan, F. F., and J. P. Jue, "Energy-awareness in dynamic traffic grooming," in *Proc. OFC, San Diego, USA*, Mar. 2010.

[271] T. Schöndienst and V. M. Vokkarane, "Renewable energy-aware grooming in IP-over-WDM networks," in *Proc. ICNC, Honolulu, USA*, Feb. 2014.

[272] A. Morea, S. Spadaro, O. Rival, J. Perelló, F. Agraz, and D. Verchère, "Power management of optoelectronic interfaces for dynamic optical networks," in *Proc. ECOC, Geneva, Switzerland*, Sep. 2011.

[273] S. Yang and F. Kuipers, "Energy-aware path selection for scheduled lightpaths in IP-over-WDM networks," in *Proc. SCVT, Ghent, Belgium*, Nov. 2011.

[274] X. Zhang and L. Xu, "Energy-efficient traffic grooming under sliding scheduled traffic model for IP over WDM optical networks," *China Communications*, vol. 11, no. 7, pp. 74–83, July 2014.

[275] E. Tego, F. Idzikowski, L. Chiaraviglio, A. Coiro, and F. Matera, "Facing the reality: validation of energy saving mechanisms on a testbed," *Hindawi JECE, Special Issue on Innovative Techniques for Power Consumption Saving in*

Telecommunication Networks, vol. 2014, no. 806960, pp. 1–11, Mar. 2014.

[276] D. Staessens *et al.*, “Definition of dynamic optical network architectures,” DICONET Project, Deliverable D2.1, Dec. 2008.

[277] A. Tymecki *et al.*, “Specification of the network scenario and service requirements,” CHRON Project, Deliverable D2.1, 2011.

[278] A. Dwivedi and R. E. Wagner, “Traffic model for USA long distance optimal network,” in *Proc. OFC, Baltimore, USA*, Mar. 2000.

[279] Cisco Systems, “Cisco visual networking index 2011-2016,” http://www.cisco.com/web/solutions/sp/vni/vni_forecast_highlights/index.html, 2012.

[280] Deutsche Telekom, “Third quarter report,” http://www.zwischenbericht.telekom.com/gb11/backstage_03/documentpool/en/en.pdf, Nov. 2011.

[281] D. Applegate and E. Cohen, “Making intra-domain routing robust to changing and uncertain traffic demands: Understanding fundamental tradeoffs,” in *Proc. ACM SIGCOMM, Karlsruhe, Germany*, Aug. 2003.

[282] M. Roughan, A. Greenberg, C. Kalmanek, M. Rumsewicz, J. Yates, and Y. Zhang, “Experience in measuring backbone traffic variability: models, metrics, measurements and meaning,” in *Proc. IMW, Marseille, France*, November 2002.

[283] M. Dale, H. Ferra, and R. Palmer, “Fast MPLS network optimisation using machine learning,” in *Proc. TENCON, Melbourne, Australia*, Nov. 2005.

[284] M. Rahman, S. Saha, U. Chengan, and A. Alfa, “IP traffic matrix estimation methods: Comparisons and improvements,” in *Proc. ICC, Istanbul, Turkey*, June 2006.

[285] S. K. Korotky, “An overview of the network global expectation model,” in *Proc. OFC, Los Angeles, USA*, Feb. 2004.

[286] A. Nucci, A. Sridharan, and N. Taft, “The problem of synthetically generating IP traffic matrices: Initial recommendations,” *ACM SIGCOMM CCR*, vol. 35, no. 3, pp. 19–32, July 2005.

[287] C. Lange and A. Gladisch, “Energy efficiency limits of load adaptive networks,” in *Proc. OFC, San Diego, USA*, Mar. 2010.

[288] ——, “Limits of Energy Efficiency Improvements by Load-Adaptive Telecommunication Network Operation,” in *Proc. CTTE, Berlin, Germany*, May 2011.

[289] Y.-W. Chen and C.-C. Chou, “Traffic modeling of a sub-network by using ARIMA,” in *Proc. ICII, Beijing, China*, Oct. 2001.

[290] B. Mukherjee, D. Banerjee, S. Ramamurthy, and A. Mukherjee, “Some principles for designing a wide-area WDM optical network,” *IEEE/ACM ToN*, vol. 4, no. 5, pp. 684–696, Oct. 1996.

[291] B. Mukherjee, *Optical WDM networks*. Springer, 2006.

[292] Y. Zhang, “6 months of abilene traffic matrices,” http://www.cs.utexas.edu/~yzhang/research/AbileneTM/, Aug. 2009.

[293] “Sndlib: library of test instances for survivable fixed telecommunication network design,” http://sndlib.zib.de/home.action, Oct. 2012.

[294] A. Somani, *Survivability and Traffic Grooming in WDM Optical Networks*. Cambridge University Press, 2006.

[295] S. Uhlig, B. Quoitin, J. Lepropre, and S. Balon, “Providing public intradomain traffic matrices to the research community,” *ACM SIGCOMM CCR*, vol. 36, no. 1, pp. 83–86, Jan. 2006.

[296] “Deutsche Forschungsnetz Verein,” http://www.dfn.de, DFN, 2010.

[297] “Amsterdam internet exchange AMS-IX,” http://www.ams-ix.net/statistics, Dec. 2014.

[298] “Internet2 networking consortium,” http://www.internet2.edu/observatory/archive/data-views.html, Sep. 2009.

[299] D. Tuncer, M. Charalambides, H. El-Ezhabi, and G. Pavlou, “A hybrid management substrate structure for adaptive network resource management,” in *Proc. NOMS, Cracow, Poland*, May 2014.

[300] “Rocketfuel: An ISP topology mapping engine,” http://www.cs.washington.edu/research/networking/rocketfuel/, Apr. 2003.

[301] W. Van Heddeghem, F. Idzikowski, F. Musumeci, A. Pattavina, B. Lannoo, D. Colle, and M. Pickavet, “A power consumption sensitivity analysis of circuit-switched versus packet-switched backbone networks,” *Elsevier ComNet*, vol. 78, no. 0, pp. 42–56, Feb. 2015.

[302] W. Van Heddeghem, F. Idzikowski, W. Vereecken, D. Colle, M. Pickavet, and P. Demeester, “Power consumption modeling in optical multilayer networks,” *Springer PNET*, vol. 24, no. 2, pp. 86–102, Oct. 2012.

[303] U. Bauknecht and F. Feller, “Dynamic resource operation and power model for IP-over-WSON networks,” in *Proc. EUNICE Workshop on Advances in Communication Networking, Chemnitz, Germany*, Aug. 2013.

[304] J. López Vizcaíno, Y. Ye, V. López, F. Jiménez, R. Duque, and P. M. Krummrich, “Cost evaluation for flexible-grid optical networks,” in *Proc. GLOBECOM, Anaheim, USA*, Dec. 2012.

[305] R. S. Tucker, “Green optical communications—part ii: Energy limitations in networks,” *IEEE JSTQE*, vol. 17, no. 2, pp. 261–274, Mar./Apr. 2011.

[306] L. A. Barroso and U. Hölzle, “The case for energy-proportional computing,” *IEEE Computer*, vol. 40, no. 12, pp. 33–37, Dec. 2007.

[307] X. Dong, T. E. H. El-Gorashi, and J. M. H. Elmirghani, “Energy-efficient IP over WDM networks with data centres,” in *Proc. ICTON, Stockholm, Sweden*, June 2011.

[308] S. Jain, A. Kumar, S. Mandal, J. Ong, L. Poutievski, A. Singh, S. Venkata, J. Wanderer, J. Zhou, M. Zhu, J. Zolla, U. Hölzle, S. Stuart, and A. Vahdat, “B4: Experience with a globally-deployed software defined WAN,” *ACM SIGCOMM CCR*, vol. 43, no. 4, pp. 3–14, Aug. 2013.

[309] L. Chiaraviglio, P. Wiatr, P. Monti, J. Chen, L. Wosinska, J. Lorincz, F. Idzikowski, and M. Listanti, “Impact of energy-efficient techniques on a device lifetime,” in *Proc. OnlineGreenComm, online conference*, Nov. 2014.

[310] B. De Salvo, G. Ghibaudo, G. Pananakakis, G. Reimbold, F. Mondond, B. Guillaumot, and P. Candelier, “Experimental and theoretical investigation of nonvolatile memory data-retention,” *IEEE ToED*, vol. 46, no. 7, pp. 1518–1524, July 1999.

[311] N. El-Sayed, I. Stefanovici, G. Amvrosiadis, A. A. Hwang, and B. Schroeder, “Temperature management in data centers: why some (might) like it hot,” *ACM SIGMETRICS PER*, vol. 40, no. 1, pp. 163–174, 2012.

[312] A. K. Coskun, R. Strong, D. M. Tullsen, and T. Simunic Rosing, “Evaluating the impact of job scheduling and power management on processor lifetime for chip multiprocessors,” *ACM SIGMETRICS PER*, vol. 37, no. 1, pp. 169–180, June 2009.

[313] L. Chiaraviglio, A. Cianfrani, A. Coiro, M. Listanti, J. Lorincz, and M. Polverini, “Increasing device lifetime in backbone networks with sleep modes,” in *Proc. SoftCOM, Primosten, Croatia*, Sep. 2013.