TREND in Energy-Aware Adaptive Routing Solutions

Filip Idzikowski,[1] Edoardo Bonetto,[2] Luca Chiaraviglio,[3,4] Antonio Cianfrani,[3,4] Angelo Coiro,[3,4] Raúl Duque,[5] Felipe Jiménez,[5] Esther Le Rouzic,[6] Francesco Musumeci,[7] Ward Van Heddeghem,[8] Jorge López Vizcaíno,[9] Yabin Ye[9]

1) Technische Universität Berlin, TKN, Berlin, Germany

2) Electronics and Telecommunications Department, Politecnico di Torino, Torino, Italy

3) Consorzio Nazionale Interuniversitario per le Telecomunicazioni, Roma, Italy

4) DIET Department, University of Roma - La Sapienza, Roma, Italy

5) Telefónica Investigación y Desarrollo SA, Madrid, Spain

6) Orange Labs, Networks and Carriers, Lannion, France

7) CNIT - Politecnico di Milano, Department of Electronics and Information, Milano, Italy

8) Department of Information Technology (INTEC) of Ghent University - iMinds, Ghent, Belgium

9) HUAWEI Technologies Duesseldorf GmbH, Munich, Germany

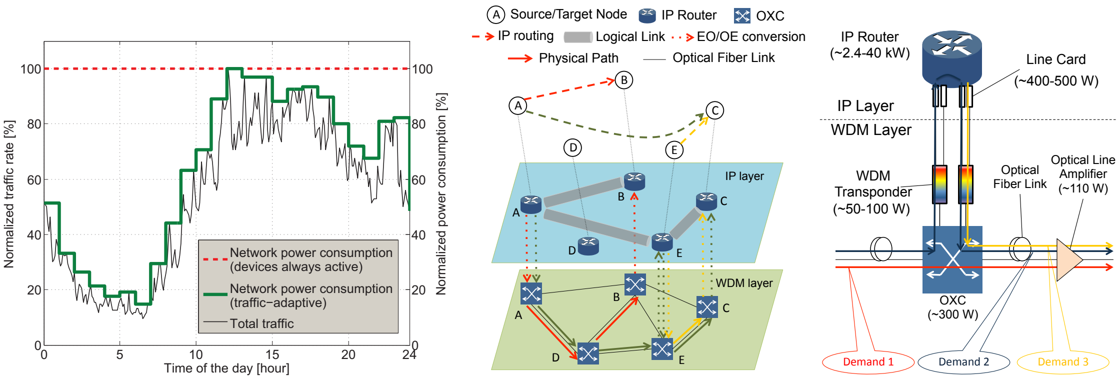
Abstract

Energy saving in telecommunications networks has become a well established topic in the research community. We look at the electrical and optical layers of IP-over-WDM networks, and present a list of evaluation criteria for the Energy-Aware Adaptive Routing Solutions (EA-ARSs) from the perspective of a network operator. Furthermore, we briefly explain the EA-ARSs originating from European Union's TREND, the FP7 Network of Excellence, show saving of energy consumed by Line Cards (LCs) on a reference scenario, and use the evaluation criteria to identify the next steps toward introduction of the EA-ARSs into real operation.

1 Introduction

The rapid increase in the number of users and high bit-rate services, such as video-streaming, cloud-computing etc., is leading operators of telecommunications networks to deploy a large number of devices. Moreover, considering that traffic is expected to substantially grow in the near future (on the order of doubling every 2 years [1]) and that the newly designed network devices do not show a corresponding improvement in their energy efficiency, it is envisioned that energy consumption will be one of the major constraints for operators. Therefore, new energy-aware solutions are needed in both the design and operation of the network so that, besides Capital Expenditures (CapEx), also Operational Expenditures (OpEx), which are substantially affected by the energy requirements, can be reduced, and an energy-bottleneck can be avoided.

In this paper we focus on the backbone section of telecom networks and jointly consider the electrical and optical layers. Although backbone networks are not the biggest power consumer in the Information and Communication Technology (ICT) sector today, their share in the overall power consumption of ICT is expected to grow due to the traffic increase [1]. Furthermore, core devices consume significant amount of power located in few nodes, which are relatively easy to manage by the network operator in comparison to access networks. We identify the challenges faced by EA-ARSs toward reduction of power consumption and present the solutions developed within the *Towards Real Energy-efficient Network Design* (TREND) project. We address the issue of how much energy can be saved by properly routing traffic demands dynamically arriving to the network and setting unused devices into low-power sleep mode or, eventually, switching them off. The EA-ARSs target day-night traffic variation. Although the traffic increases also in



(a) Traffic and normalized power over a day (b) Network model (c) Node and link models

Figure 1: (a) Normalized traffic variation over a working day in FT network, and theoretical normalized power consumption with always-active devices or when traffic-adaptive routing is adopted. (b) Multilayer network architecture. (c) Node and link components.

the long term, the network dimensioning is out of scope of this work.

An example of day-night traffic variation is shown in Fig. 1(a) (thin continuous line) depicting how the total traffic volume (normalized to the peak traffic) changes with time, as measured within the France Telecom (FT) network. It can be seen that traffic changes substantially, and the traffic volume during off-peak hours is up to 90% lower than the maximum. In this situation, routing traffic demands in an energy-aware fashion and switching off unused devices may lead to substantial energy savings. Indeed, in Fig. 1(a) we also schematically show the network power consumption (normalized to the maximum) obtained when all the network devices are active regardless of the current traffic carried by the network (dashed line), and when traffic-adaptive solutions are exploited for routing demands (thick continuous step-line). The idea is to let the total power consumption follow the trend of traffic variations, in order to have power savings which reflect the reduction experienced by the overall network load during the day.

Network model In the following we consider an Internet Protocol (IP)-over-Wavelength Division Multiplexing (WDM) network model (Fig. 1(b)) in which the IP layer, where traffic demands are originated and terminated by IP routers, constitutes the logical topology and is placed over the WDM layer, where Optical Cross-Connects (OXCs) are interconnected through optical fiber links and constitute the network physical topology. An additional layer is drawn in the figure to show the IP routing (dashed arrows) of end-to-end traffic demands between source/target nodes.

The IP routing of each demand is mapped over one or more consecutive logical links, represented with pipes in the IP layer in Fig. 1(b). Every logical link between two nodes, say A and B, consists of a bundle of parallel lightpaths (concatenations of wavelength channels) initiated/terminated in the IP layer by routers A and B. Thus the capacity of each logical link corresponds to the number of parallel lightpaths between its source and target nodes. Moreover, lightpaths traverse physical paths in the physical topology (solid arrows in the WDM layer), i.e., a set of optical fiber links. Vertical dotted arrows are drawn in the figure to represent the optical signals flowing between the IP routers and the OXCs, corresponding to Electrical-Optical (EO) or Optical-Electrical (OE) conversion.

The source-target IP routes typically traverse multiple hops in the logical topology in order to efficiently exploit wavelength capacity. An example is shown in the figure for the demand between nodes A and C, which traverses the two logical links A-E and E-C. Node E is the grooming site where traffic belonging to the demand A-C is aggregated with traffic belonging to the demand E-C.

As shown in Fig. 1(c), every node consists of an IP router connected to an OXC through several gray LCs and WDM transponders. At the WDM layer, optical signals are switched by the OXC (possibly equipped with wavelength converters) toward the proper output ports. Optical fiber links are equipped with

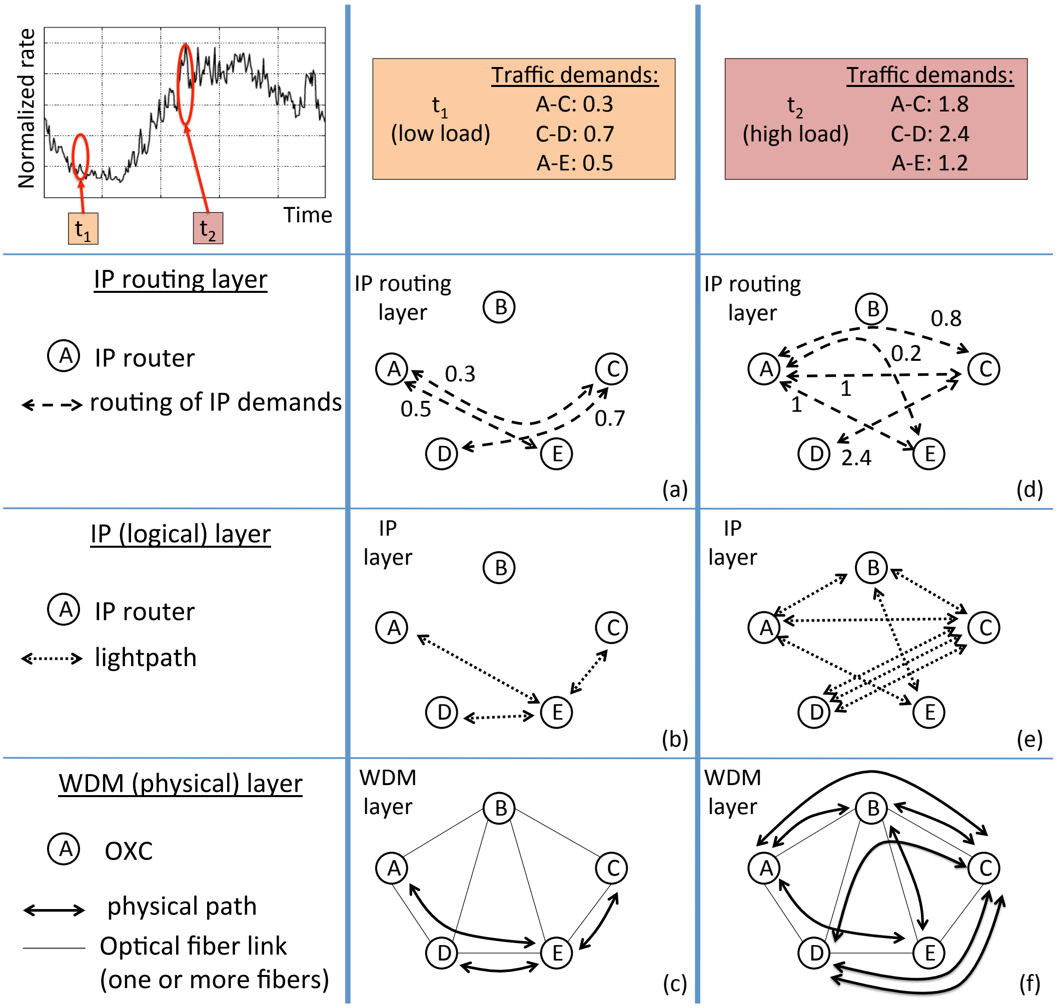


Figure 2: Example of routing adaptivity to traffic changes. IP routing of source-target demands, established lightpaths and their routing for the low traffic (t_1, figures a-b-c) and high traffic (t_2, figures d-e-f) scenarios.

Optical Line Amplifiers (OLAs) (usually Erbium Doped Fiber Amplifiers (EDFAs)) needed to restore the signal power level[1]. Each device has a different relevance to the total power consumption of the network, as indicated in Fig. 1(c) (see [2] for the specific power values).

In Fig. 1(c) we also show that in the nodes the lightpaths can be either switched directly in the optical domain, thus bypassing the IP router (as happens for the lightpath carrying Demand 1), or terminated, in order to accomplish traffic grooming (as for the lightpath carrying Demands 2 and 3). Indeed, traffic grooming has already been demonstrated to be useful not only to efficiently exploit wavelengths capacity, but also to save energy, since it allows to switch off many unused LCs and avoid large amount of electronic traffic processing, which are known to be power-hungry (see [3] and the references therein).

Routing adaptivity to traffic variations An example of routing adaptivity to temporal traffic variation is shown in Fig. 2, which depicts how the IP routing (dashed arrows in Figs. 2(a) and (d)), the established lightpaths (dotted arrows in Figs. 2(b) and (e)) and the WDM layer routing (continuous arrows in Figs. 2(c) and (f)) are accomplished according to traffic requirements. At the top of the figure we report the traffic behavior from Fig. 1(a) and identify two time instants, t_1 and t_2, as the occurrence of triggering events

[1] Note that two additional amplifiers (pre-amplifier and booster, not shown in Fig. 1(c)) are placed at the edges of every fiber link.

(e.g., a certain traffic threshold is reached) for potential network reconfiguration. We also show exemplary values of the traffic demands in t_1 and t_2, expressed in units normalized to the capacity of a lightpath. In t_1 (say, at night) the bandwidth required by the network is low. As the time goes on, the traffic requirements increase, until instant t_2, where new lightpaths are established, routing of IP demands is adapted to the current traffic and, eventually, some lightpaths are torn down to reduce the energy consumption.

Organization of the article The remainder of this article is organized as follows. In Section 2 we provide a brief overview of the aspects of EA-ARSs in "green" backbone networks which are currently under investigation besides TREND. Challenges posed by network operators to the EA-ARSs are identified in Section 3. In Section 4 we discuss the different EA-ARSs at both the IP and WDM layers proposed within TREND and provide an evaluation of energy savings. Finally, in Section 5 we draw conclusions by revisiting challenges posed by the network operators and identifying the steps that have been made and that are still needed toward standardization and real use of the EA-ARSs.

2 Related work

The first work presenting the idea of EA-ARSs was [4], in which Gupta and Singh advocated the need of a green Internet. Since then, different works have tackled the problem of energy-efficient backbone networks (see [5, 6] for detailed surveys).

Table 1 provides an overview of different projects focussing partially or entirely on EA-ARSs.

Overall, all these activities prove that there is a substantial engagement of the research community in the field of EA-ARSs. However, TREND presents unique features. In particular, TREND acts as a center of excellence, working as a communication hub between the research projects. Specifically, TREND enforces the cooperation and the dissemination of information, with the aim of integrating the research efforts among its partners but also among the other projects. As a second feature, TREND investigates different solutions for energy-aware routing. Assurance of the Quality of Service (QoS) in the energy-aware routing is a complex problem, that has to be investigated at different layers, and with different strategies. Therefore, we have developed a set of algorithms rather than a single solution. Furthermore, we have defined a set of criteria to evaluate the algorithms based on feedback from network operators. All these features are essential to providing guidelines for an energy-aware evolution of the Internet.

3 Evaluation criteria for EA-ARSs

Dynamic adaptation of the network to actual traffic needs could significantly decrease overall power consumption with respect to the current situation, where no power-driven routing algorithms or power management procedures (sleep modes) are deployed. The potential of these new techniques will be dependent on their suitability to major operator challenges. We have identified a set of criteria that are particularly relevant to telecom operators for evaluation of potential solutions. These criteria are listed in Table 2, and explained in more detail below. In the next section, we will discuss EA-ARSs proposed within the TREND project according to these criteria.

The core segment is, by far, the most critical one of the global telecommunications company network. Very high performance routers are connected through optical pipes carrying extremely big volumes of traffic, so that a failure or instability could have fatal consequences. Power-aware routing mechanisms must consider all the classical constraints to be found in optical transport deployments, like maximum lightpath length and wavelength continuity across transparent domains **(C1)**.

Constraints on installed devices (e.g., routers, OXCs and OLAs) should be considered as well – solutions preferably should not require additional equipment to be installed **(C2)**. E.g., if a certain node in the network is equipped with 16 LCs, the solution should make sure that after reconfiguration the amount of required LCs in that node remains limited to 16.

Table 1: Recent projects related to Energy-Aware Adaptive Routing Solutions (EA-ARSs)

Project	Type	Duration	Scope	Relevance to EA-ARSs
TREND (`http://www.fp7-trend.eu/`)	European Network of Excellence	09/2010-11/2013	Design of energy-efficient networks by integrating the activities of major European players in networking.	Energy-efficient design of core networks, algorithms for the energy-aware management of IP and optical networks.
ECONET (`http://www.econet-project.eu/`)	European Integrated Project	10/2010-09/2013	Design of energy-sustainable wired network equipment and infrastructures.	Green strategies in the control plane, algorithms and routing protocols to allow autonomic and distributed network reconfigurations.
GreenTouch (`http://www.greentouch.org/`)	International Consortium	01/2010-ongoing	Rethinking communications and data networks to significantly reduce the carbon footprint of the ICT sector.	Power saving architectures for the IP and the optical layers.
STRONGEST (`http://www.ict-strongest.eu/`)	European Integrated Project	01/2010-12/2012	Design of next generation ultra-high capacity multi-layer transport network.	Design of new network architectures while reducing network energy consumption.
GEYSERS (`http://www.geysers.eu/`)	European Integrated Project	01/2010-12/2012	Development and validation of an end-to-end network architecture composed of virtual infrastructures.	Metrics to reduce energy consumption along end-to-end path, optimized network routing.
CHRON (`http://www.ict-chron.eu/`)	European Specific Targeted Research Project	07/2010-06/2013	Design of a new optical architecture and a control plane to efficiently use network resources.	Providing effective decisions on routing, resource assignments and switching off and on of network elements.
COST Action IC0804 (`http://www.cost804.org/`)	European Cooperation in Science and Technology	01/2009-05/2013	Increase of the overall impact of European research in the field of energy efficiency in distributed systems.	Energy-efficient solutions for wired networks, by coordinating the actions of individual devices to reduce globally the energy consumption.

Simplicity and reliability are the main core network features that have to be maintained if dynamic power adaptation mechanisms are introduced. Impact on QoS (service disruptions, packet loss, delay, etc.) must be negligible or, preferably, totally avoided, as it will have an impact on the performance and Quality of Experience (QoE) offered to the end users and will raise supervision and maintenance expenses **(C3)**.

The time required for a device to go into sleep mode and wake up have to be taken into account to avoid temporary failures. Consequently traffic margins need to be considered for powering on (to be done before capacity is actually needed) and powering off (to be done some time after capacity is not needed anymore) of network devices. Computation time, i.e., the time needed to run power adaptation algorithms, is also a relevant parameter for both the frequency of reconfigurations and their procedures **(C4)**.

An adequate procedure must be followed at switching on/off events for a generic client (i.e., IP) and line (i.e., optical) side to prevent from any traffic loss. Events triggering the execution of the algorithms (e.g., end of an observation period, or hitting thresholds on link load) need to be carefully chosen and parametrized **(C5)** in order to leave appropriate security margins that minimize the chance of traffic interruption. A switch-off must be done after checking that traffic can be safely absorbed over remaining resources while a switch-on must be done in advance, to cope with a future traffic increase.

The centralized or distributed operation **(C6)** of the algorithm is important from the perspective of a network operator. No matter whether an algorithm is run centrally or in a distributed way, it may require either local or (some) global knowledge of the network **(C7)**. The following aspects constitute the knowl-

Table 2: Evaluation criteria for Energy-Aware Adaptive Routing Solutions (EA-ARSs)

No.	Criterion	Short description
C1	Physical layer constraints	Does the solution take into account the classical physical layer constraints found in optical transport deployments (such as maximum length of a lightpath)?
C2	Constraints on installed devices	Does the solution adhere to the number of installed devices, or does reconfiguration potentially require additional devices to be installed?
C3	Impact on QoS	Does the solution consider its impact on the QoS?
C4	Computation time	What is the solution's algorithmic computation time?
C5	Triggering events	Which events trigger network reconfiguration?
C6	Operation	Is the solution based on a centralized or a distributed algorithm?
C7	Network knowledge	What information about the network (local or global) is needed for the solutions to gather information about the state of the network (including knowledge of the complete Traffic Matrix (TM))?
C8	Protection consideration	Is the impact on protection (availability, Mean Time To Repair (MTTR) and Mean Time Between Failures (MTBF)) considered?
C9	Reconfiguration cost	Does the solution consider the reconfiguration cost between two consecutive time periods?
C10	Future traffic assumption	Does the evaluation study of the solution assume knowledge of future traffic demands between all node pairs in the network?
C11	Control mechanism	Does the solution consider an (existing) mechanism to control the changes that are required by the output of the EA-ARS, such as Multi-Protocol Label Switching Traffic Engineering (MPLS-TE)?

edge of the network: $i/$ complete TM; $ii/$ routing of IP traffic demands over the logical topology; $iii/$ physical topology and installed devices; $iv/$ available wavelengths and routing of lightpaths (including physical constraints); $v/$ load on the logical links (which can be computed from i and ii).

Dynamic mechanisms must be aware that overdimensioning is required for protection **(C8)** and QoS and a comprehensive view of the overall multilayer network (e.g., IP-over-WDM) would be needed before making a power on/off decision. This global view of the network is critical to ensure permanent service availability under any situation potentially reachable when power saving mechanisms are applied.

Fig. 3 shows an example highlighting the need of a multilayer view to avoid potential service disruptions with EA-ARSs. The figure reflects a situation where a traffic demand TD1 from router B to router E is carried over a direct (single-hop) logical link between IP routers, that is composed of a maximum of two lightpaths each of capacity L. There is also a traffic demand TD2 between router A and router E traversing router C, that is protected (at IP layer) through router B. Lightpaths are released if they are empty and load on parallel lightpaths is lower than $0.8L$. In *Case a*, TD1 is higher than $0.8L$ and two lightpaths are active, therefore TD2 can be accommodated over the remaining capacity if a failure occurs on the A-E working route. In *Case b*, TD1 has decreased to less than $0.8L$ and one lightpath is switched off, in order to avoid unnecessary power consumption. Finally, in *Case c*, there is a failure on A-E route (router C crashes), and A starts sending packets to E via B using the backup route. In this situation, if power-saving mechanisms do not have a multilayer view (IP and optical), the B-E logical link now having just one lightpath will be short of capacity to carry both TD1 and TD2, and some traffic will be dropped.

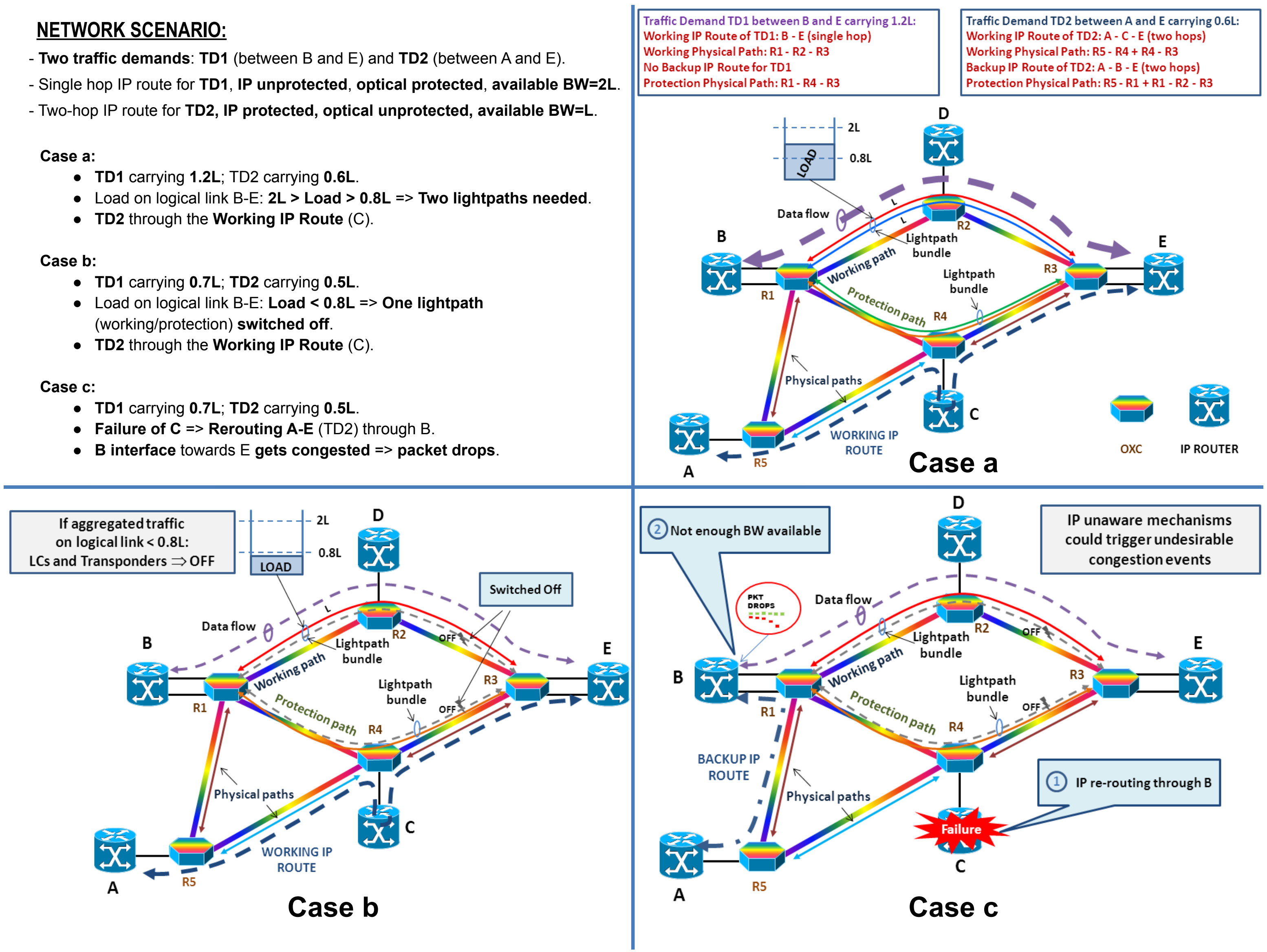


Figure 3: The need for multi-layer awareness in the context of protection.

Deployment of dynamic EA-ARSs should ideally maintain the same level of resiliency of current energy-unaware networks to get full acceptance by network operators. EA-ARSs should take into account reconfiguration costs, meaning any changes or modifications in the network that could have a negative impact on its behavior, as well as the time and energy needed for them to be completed **(C9)**.

A major practical difficulty for actual deployment of EA-ARSs lies in the fact that future traffic is unknown during the computation **(C10)**. Even if the computation is triggered using up-to-date traffic measurements, traffic burstiness in the core is limited and future traffic increase or decrease is estimated based on historical data, traditional overprovisioning is still needed to cover the unexpected traffic increase. Assuming known future traffic by the EA-ARSs corresponds to an upper bound of energy savings.

Finally, commercial telecommunications networks must have a high degree of automation that makes them highly scalable and easy to operate. This means that a mechanism able to control the changes required by the power-aware routing solutions will be needed for commercial deployments **(C11)**.

4 TREND contribution to EA-ARSs

Several algorithms targeting saving energy in the IP and optical layers have been proposed within TREND. We briefly explain their main principles referring the readers to the corresponding publications for details.

4.1 Saving energy in the IP layer

The computationally simplest approach to save energy is to deactivate idle devices utilizing only the traffic variation and no IP rerouting. This is the main idea of **Fixed Upper Fixed Lower (FUFL)** [6, 7] which does not change the routing of IP traffic demands and of lightpaths, and powers off/on the LCs according to the changing traffic.

Least Flow Algorithm (LFA) and **Most Power Algorithm (MPA)** described in [8] attempt to power off entire logical links, with the corresponding LCs, and possibly also routers, checking if the network is still connected and all IP traffic demands are satisfied according to the updated IP routing. The only difference between the two algorithms is the order in which resources are considered, either according to increasing load or power. The ordering issue has been improved in **L-Game** [9]. The logical links are ordered according to a measure (Shapley value) that defines how much a link is critical, meaning how much traffic can not be routed if this link is not active.

The previous algorithms do not take into account any cost related to the reconfiguration of the network. Instead, the **Genetic Algorithm (GA)** [10] searches through random selection, crossover and mutation for a feasible logical topology (which acts as an individual) that reduces not only the power consumption, but also the amount of IP traffic that has to be rerouted between two consecutive time periods.

Differently from GA, the **Energy Watermark Algorithm (EWA)** [11] does not compute an entirely new logical topology, but it gradually modifies the current one according to the utilization of the lightpaths on logical links. It uses two thresholds (watermarks), to detect if a link is highly loaded or underutilized, and activates or deactivates lightpaths with corresponding LCs accordingly.

Virtual Line Card Migration (VLCM) [12] is a solution that does not modify the topology of the network at the IP level (i.e., the logical topology), but changes the topology at the Multi-Protocol Label Switching (MPLS)/Ethernet level. This is possible by virtualizing the IP logical functionalities, which means moving the IP functionalities from a LC to another one, allowing then to put the first LC into idle state.

Distributed and Adaptive Interface Switch-off for Internet Energy Saving (DAISIES) [13] is another solution that exploits the control mechanisms provided by MPLS to switch off router LCs. The actual amount of traffic carried by each Label Switched Path (LSP) is monitored by the ingress node on a fine granular observation period (e.g., tens of seconds). Then, whenever it goes beyond a prefixed threshold, the ingress node recomputes the path of the LSP and reroutes it updating both the path and the reserved bandwidth (make-before-break). The information about available (unreserved) bandwidth advertised by the Traffic Engineering (TE) routing protocol is used by DAISIES to properly compute link weights, and in turn aggregate the traffic on a reduced set of links.

4.2 Saving energy in the optical layer

Two main approaches are proposed in TREND to increase the energy efficiency of the optical layer. The first one, referred to as Power-Aware Routing and Wavelength Assignment (PA-RWA) [14], represents an enhancement of the well known strategies for lightpath route computation and wavelength assignment in the classical WDM networks. In the first step of PA-RWA called **Load Based Cost (LBC)**, a shortest path algorithm solves the routing subproblem using a dynamic load-dependent function to associate a weight to each optical fiber link. In the second step (**Least Cost Wavelength (LCW)**), wavelength assignment is performed considering the load state and the power consumption of the OLAs deployed along the fibers. LCW assigns a cost to each wavelength available on the links belonging to the path computed by LBC, and chooses the wavelength minimizing the cost on the whole path.

The second approach investigates the impact of the innovative Elastic Orthogonal Frequency Division Multiplexing (OFDM)-based network on the energy consumption of optical networks by considering only the elements in the WDM layer of Fig. 1, but with the main distinction of employing bandwidth-variable transponders (OFDM transponders) and bandwidth-variable OXCs, instead of the WDM transponders and fixed-grid OXCs used in the conventional WDM networks. With respect to classical WDM networks, where the coarse granularity of a wavelength and the rigid channel spacing specified by the ITU-T grid may lead to an inefficient use of the spectral resources, the elastic OFDM-based network allows for a more flexible and dynamic allocation of network resources making use of the coherent optical OFDM transmission technology. This modulation technique allows for two levels of flexibility to better adjust the transmission rate to the actual demand: $i/$ an elastic transmission bandwidth, by selecting a variable number of subcarriers, and $ii/$ the employment of different modulation formats for subcarriers (distance-adaptive modulation possibility). Two energy-aware heuristic algorithms for the routing and resource allocation of the dynamic traffic demands are proposed in [15], i.e., **Energy-Aware Routing and Wavelength Assignment (EA-RWA)** and **Energy-Aware Routing, Modulation Level and Spectrum Allocation (EA-RMLSA)**. The power consumption of the network elements is used as a link weight to select the most energy-efficient lightpath from a set of k-shortest paths. EA-RMLSA utilizes the two levels of flexibility mentioned above, while different combinations of available Mixed Line Rates (MLRs) are considered in EA-RWA.

4.3 Overview of the proposed algorithms

All the algorithms presented in Sections 4.1 and 4.2 are summarized in Table 3 according to the criteria presented in Table 2. The second column of the table reports the devices that can be potentially switched off to save energy. LCs are the most frequently targeted devices, since their switching on and off is expected to be relatively quick. Evaluation of some algorithms does not take into account the constraints of the physical layer (**C1**), but all algorithms mind the number of installed devices (**C2**). Although some algorithms do not explicitly take into account the impact of the energy saving on the QoS **(C3)**, some studies analyze corresponding metrics (e.g., Service Blocking Ratio in [15]). Since computation time **(C4)** depends on the network size, parametrization of the algorithms, the platform used for the computation, and the actual implementation, we present the worst case algorithm complexity as a function of the following parameters: the number of nodes (N), the number of logical links (L), the number of wavelengths per fiber (W, corresponding to the number of subcarriers for EA-RMLSA), and algorithm-specific input parameters (M, K, S for GA [10], the number of candidate paths k in EA-RWA and EA-RMLSA [15], and F denoting the number of possible line rate combinations or modulation formats for EA-RWA and EA-RMLSA respectively [15]). The actual computation time varies, e.g., depending on the traffic conditions in EWA.

Table 3: Classification of TREND Energy-Aware Adaptive Routing Solutions (EA-ARSs)

Algorithm Name	Targeted Devices	Physical layer constraints (C1)	Constraints on installed devices (C2)	Impact on QoS (C3)	Computation time (C4)	Triggering events (C5)	Operation (C6)	Network knowledge (C7)	Protection considered (C8)	Reconfiguration cost (C9)	Future traffic assumption (C10)	Control mechanisms (C11)
FUFL [6, 7]	LCs & transponders (lightpaths)	Considered (all constraints)	Included (all devices)	Over-provisioning	$\mathcal{O}(1)$	Exceeding utilization thresholds	Distr.	Local	No	No reconfiguration	Known [6, 7]	Not needed
LFA / MPA [8, 10]	Routers, LCs & transp. (IP links)	Not considered	Included (all devices)	Over-provisioning	$\mathcal{O}(LN^2 + L \cdot logL)$	Change of TM	Centr.	Global	No	Not considered	Known [8, 10]	Not considered
L-Game [9]	LCs & transp. (IP links)	Not considered	Included (all devices)	Shapley value	$\mathcal{O}(LN^2 + L \cdot logL)$	Change of TM	Centr.	Global	No	Not considered	Known [9]	Not considered
GA [10]	LCs & transponders (lightpaths)	Not considered	Included (routers and LCs)	Over-provisioning	$\mathcal{O}(M \cdot K \cdot S \cdot N^2)$	Change of TM	Centr.	Global	No	Rerouted traffic	Known [10]	Not considered
EWA [10, 11]	LCs & transponders (lightpaths)	Not considered	Included (routers and LCs)	Over-provisioning	$\mathcal{O}(L^3N^2)$	Exceeding utilization thresholds	Centr.	Global	No	Prev. network config. usage	Unknown [11], known [10]	Not considered
VLCM [12]	LCs & transponders (IP links)	Not considered	Included (routers and LCs)	IP transparency	$\mathcal{O}(LN^2)$	Change of IP traffic demand	Centr.	Global	No	Not considered	Known [12]	Not considered
DAISIES [13]	LCs & transponders (lightpaths)	Not considered	Included (routers and LCs)	Over-provisioning	$\mathcal{O}(N^3)$	Change of IP traffic demand	Distr.	Global	No	Not considered	Unknown [13, 14]	MPLS rerouting
LBC - LCW [14]	OLAs	Considered (wavel. assign.)	Included (OXCs, transp., fibers with OLAs)	Not considered	$\mathcal{O}(N^2 + N \cdot W)$	Change of TM	Distr.	Global	No	Not considered	Unknown [14]	Not considered
EA-RMLSA (Elastic OFDM) / EA-RWA (MLR WDM) [15]	Transponders, OXCs	Considered (lightpath length)	Included (OXCs, transponders, regenerators, fibers with OLAs)	Not considered	$\mathcal{O}(k \cdot F \cdot W \cdot N^3)$	New IP traffic demand, and its termination	Centr.	Global	No	Not considered	Unknown [15]	Not considered

The triggering events **(C5)** are related to either the whole TM, or a single traffic demand, or utilization of logical links. All these events depend however on the length of the observation period. Most of the proposed solutions work in a centralized manner **(C6)** and need global (to various extents) knowledge of the network **(C7)**, however the control mechanism **(C11)** was considered only in [13] (DAISIES). Two algorithms directly address reconfiguration costs **(C9)** which should reduce the amount of signaling and control messages exchanged in the network. Moreover, the simple mechanism FUFL does not require any reconfiguration at all (apart from switching LCs and transponders on and off based on local decisions). While overprovisioning seems to be the most popular mechanism to reduce the impact of the energy-aware routing solution on the QoS, none of the proposed solutions considers protection **(C8)**. Moreover, some works assume knowledge of future traffic **(C10)**, which is however a parametrization issue.

The actual energy savings depend on several factors:

1. Baseline power consumption of the Static Base Network (SBN) including the overprovisioning
2. Traffic assumptions including variation over time and the total load
3. Properties of the network topologies such as nodal degree
4. Assumed power values of single devices in the active and sleep modes
5. The layer(s) that the EA-ARS targets

In order to provide a fair comparison with respect to the points above, we selected the reference network (38 nodes, 72 logical links) with corresponding traffic data defined by FT for the year 2020 [7] and applied a subset of the EA-ARSs working in the IP layer to it. The SBN was dimensioned using the same method as in [10] with the objective of CapEx minimization and the Maximum Utilization of Each Logical Link (MUELL) equal to 0.5 under peak traffic [6]. The energy consumed by active LCs is calculated over a working day (Fig. 1(a)) with medium traffic assumption [7]. Energy savings against the SBN are presented in Table 4 together with parametrization of the algorithms and their references. We varied the constraint on the targeted MUELL in the algorithms. We set it either to 0.5 or to 1.0 with the first value being identical to MUELL in the SBN dimensioning. Improved versions of LFA and MPA were used in this study with respect to [8, 10]. In particular, we consider to switch off single lightpaths rather than complete logical links. The results show that all the algorithms provide significant energy saving with respect to energy consumed by all LCs in the SBN even if MUELL is constrained to 0.5. The simplest mechanism FUFL achieves the lowest savings, but requires only local network knowledge and no dynamic control mechanisms. The other mechanisms achieve similar energy savings and can be favored by the fulfillment of the evaluation criteria from Table 2. Furthermore, traffic on a weekend day is lower than on a working day [7], so the energy savings on such days will be higher. Please, note that the savings reported in Table 4 refer to LCs, and the other network equipment (chassis, switch matrix, control, power supply, cooling, OLAs, etc.) is not included, so the overall energy savings may differ considerably from the figures given here.

We estimate that the proposed algorithms will have an impact on two main kinds of technologies: first the devices themselves should be able to support sleep mode or at least frequent on-off cycling, and second the control plane should be able to automate the network in dynamic reconfiguration.

Ensuring that devices support frequent on-off (sleep mode) cycling may require novel specifications and reliability tests. Standardization efforts may be needed to precisely define the sleep modes of the considered devices. Similarly to what is proposed for Passive Optical Networks (PONs) (power shedding, dozing, cyclic sleep and deep sleep in the ITU-T G.sup 45) different sleep modes may exist with different power consumption, fall asleep times or wake up times, and some algorithms may require this information in order to provide the proper rerouting result. All the proposed algorithms require information about traffic and load on the different devices. This information, if global, requires specific control messages to be distributed to other nodes or to the central computing/control element. Standard protocols such as Generalized Multi-Protocol Label Switching (GMPLS) control plane with a Path Computation Element are already capable of such information distribution and we do not expect major impact on control plane

Table 4: Saving of energy consumed by Line Cards (LCs) with respect to the Static Base Network (SBN) over a working day, FT reference scenario (i.e., network and corresponding traffic data) defined in [7]

Algorithm	MUELL		Parameters deviating from [10] for the two values of Maximum
	0.5	1.0	Utilization of Each Logical Link (MUELL=0.5) and (MUELL=1.0)
FUFL	15%	57%	($W_D = 0.4$, $W_A = 0.5$) and ($W_D = 0.8$, $W_A = 0.9$) [7]
LFA	43%	67%	No parameters except for MUELL [8, 10]
MPA	42%	66%	No parameters except for MUELL [8]
GA	43%	66%	For both values of MUELL: $\alpha = 0.1, M = 50, S = 30, K = 20$ [10]
EWA	43%	68%	($W_L = 0.1$, $W_H = \psi = 0.5$) and ($W_L = 0.1$, $W_H = \psi = 0.9$) [10]
VLCM	39%	62%	No parameters except for MUELL [12]
DAISIES	45%	70%	For both values of MUELL: $\Delta_f^{\%} = 0.06$ [13]

message exchange, except for the definition of dedicated messages in case specific information (such as information about the events that trigger the re-routing – e.g., load thresholds, the type of sleep mode capability, ...) is missing. It seems also mandatory that all the algorithms benefit from a multi-layer capable control. They should be aware of the capacity offered by the lower layers in order to maintain a high level of service quality and availability. This may also have an impact on control plane and specific extension may be required. Although none of our studies considered multiple domains, this may also be a case for specific control plane extension.

5 Conclusion

EA-ARSs are a promising way toward reduction of energy consumption in the electrical and optical layers of core networks. We showed with a subset of algorithms working in the IP layer that significant saving of energy consumed by LCs can be achieved. Moreover, we analyzed solutions proposed within TREND in the light of the eleven evaluation criteria identified in this work. It turned out that many of the criteria are already fulfilled (e.g., reduction of reconfiguration costs, complexity and the amount of knowledge about the network, addressing the impact on QoS). There are however some remaining open issues in each of the proposed EA-ARSs, e.g., taking into account physical constraints in EWA or addressing impact on QoS in EA-RMLSA. While some issues can be tackled disjointly from the EA-ARS (e.g., forecasting of future traffic or control mechanisms), protection remains the biggest open issue, which has not been explicitly addressed by any of the proposed solutions. Taking into account particularly computation time, operation and reconfiguration cost, DAISIES, EWA and FUFL seem to be the most promising and realistic solutions in the IP layer. In the optical layer, elastic solutions offer much flexibility, and are currently intensively investigated by the research community.

Future work should therefore focus on how to change the configuration of the energy-aware network, in order to provide low MTTRs. E.g., multi-path routing could be a way of protection against failure in the sense that source-target communications will be maintained with limited resources in the case of a failure.

Once an EA-ARS fulfilling all the evaluation criteria is found, a few other issues independent of the EA-ARS need to be completed before standardization. They include implementation of sleep mode capable devices, reduction of time needed to power on and power off the devices, and reliability of the network devices being frequently switched on and off (increasing MTBF). Moreover, the control mechanisms may be subject for improvement in order to guarantee smaller reconfiguration times of the network.

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