◆ Protocol Enhancements for "Greening" Optical Networks

Annalisa Morea, Jordi Perelló, Salvatore Spadaro, Dominique Verchère, and Martin Vigoureux

The last decade has spurred a number of research efforts around energy efficiency in information and communication technologies (ICT). To reduce the energy consumed by optical transport networks, one option is to switch-off a certain number of optical systems according to the amount of transported traffic. Consequently, dynamic power management of optoelectronic devices and link sleep-mode approaches have been proposed; these capabilities quantitatively optimize the power requirements and the available bandwidth of the network as a whole. This paper presents enhancements embedded in Generalized Multiprotocol Label Switching (GMPLS)-based protocols enabling power control in optical devices, and then analyzes the impact of controlling the daily energy consumption of optical switching equipment in the network. We also present ongoing activities in specific standardization working groups for "greening the network" along with their proposals to improve the energy efficiency of future optical networks. © 2013 Alcatel-Lucent.

Introduction

In the last few years, diverse reports have described the steep increase of energy consumption in the information and communication technologies (ICT) sector. In 2007, energy consumption in the ICT sector accounted for two percent of the total energy consumption in the world [31]. **Figure 1** shows the yearly energy consumption for a number of major European telecom operators. Increases range from one percent to 120 percent, with an average increase of 13 percent per year. The points on the graph were obtained by considering the yearly energy consumption of network operators reported in [8, 15, 17, 41]. The reason for this steep increase in energy consumption is attributed to technology development (faster and more power-hungry equipment), higher transmission volumes (the expanding number of services offered by providers [26], such as streaming and video-on-demand) and network expansion (growth of the customer population [6]).

In [16], the European Commission reported estimates of overall consumption by some European operators, pointing out that if energy consumption was equal to 14.2 TWh in 2005 and 21.4 TWh in 2010, that it will reach 35.8 TWh in 2020 if there is no resolution on improving energy efficiency in the network.

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Panel 1. Abbreviations, Acronyms, and Terms

ANSI—American National Standards Institute
CG—Connectivity graph
CO_2—Carbon dioxide
COST—European Cooperation in the field of Scientific and Technical Research
DMTF—Distributed Management Task Force
ECONET—Energy COnsumption NETworks
EDFA—Erbium doped fiber amplifier
EMAN—Energy MANagement
EnMS—Energy management system
EON—European Optical Network
ETSI—European Telecommunications Standards Institute
FEC—Forward error correction
GMPLS—Generalized Multiprotocol Label Switching
HALF-MOON—Highly Adaptive Layer for Meshed On-Off Optical Networks
HSM—Hybrid sleep-mode
ICT—Information and communication technologies
IEC—International Electrotechnical Commission
IEEE—Institute of Electrical and Electronics Engineers
IETF—Internet Engineering Task Force
IP—Integrated project
IP—Internet Protocol
IRTF—Internet Research Task Force
ITU—International Telecommunication Union
ITU-T—ITU Telecommunication Standardization Sector
LMP—Link Management Protocol
LSM—Link sleep-mode
LSP—Label-switched path
MIB—Management information base
MILP—Mixed integer linear program
NMS—Network management system
OE—Optoelectronic
OESM—OE device sleep-mode
OSPF—Open Shortest Path First
PC—Personal computer
PDM—Polarization division multiplexing
QPSK—Quadrature phase shift keying
REG—Regenerator
RSVP-TE—Resource Reservation Protocol-Traffic Engineering
RWA—Routing, wavelength assignment
SNMP—Simple Network Management Protocol
TSP—Transponder
WDM—Wavelength division multiplexing

The need for more energy-efficient network solutions, also called *green networking*, is twofold, impacting both the environment as well as the world economy. Environmental efforts aim at reducing wasted energy as well as CO_2 emissions [14], while economic efforts focus on curtailing costs due to continuously rising energy prices coupled with the telecom operators' goal of network sustainability at a lower cost.

One solution for reducing energy consumption in the network is the introduction of novel low consumption technologies, usually silicon-based. Nevertheless, it has been demonstrated that silicon technologies improve their energy efficiency at a rate following Dennard's scaling law (x1.65/18 months) [5], much lower than the rate at which the traffic load is increasing, which follows Moore's law (x2/18months) [43], and the previously computed rate at which costs for energy are increasing (x1.36/18months). Hence, new paradigms for getting greener networks have been proposed in the realms of both network and system design (i.e., disruptive architectural and equipment and device solutions) and operational management (i.e., protocol improvements), acting at both the device and network levels.

To encourage network providers and operators to "green" their networks, the International Telecommunication Union (ITU) seeks to foster sustainable development and promote energy efficiency with recommendations [24] and guidelines [23]. The ITU believes that telecom operators and service providers are moving towards energy-efficient networks mainly because of the relative cost savings provided by the new concepts.

Many studies have dealt with energy conservation in telecom networks; a survey is provided in [5]. The research and development approaches

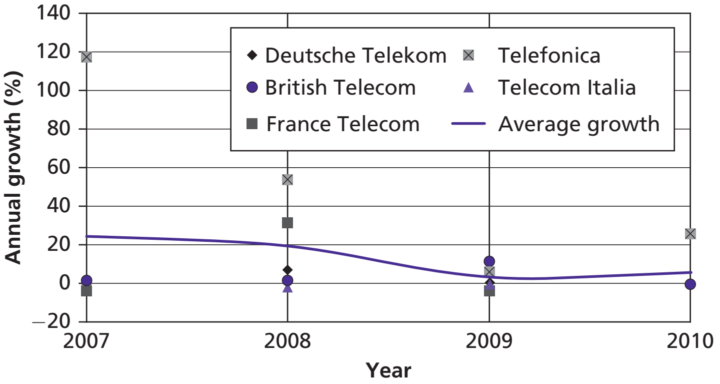


Figure 1.
Yearly energy consumption increase of some of the major European telecom operators.

range from energy-saving techniques for networked hosts, to technologies and mechanisms for designing next-generation energy-aware networks and equipment [12].

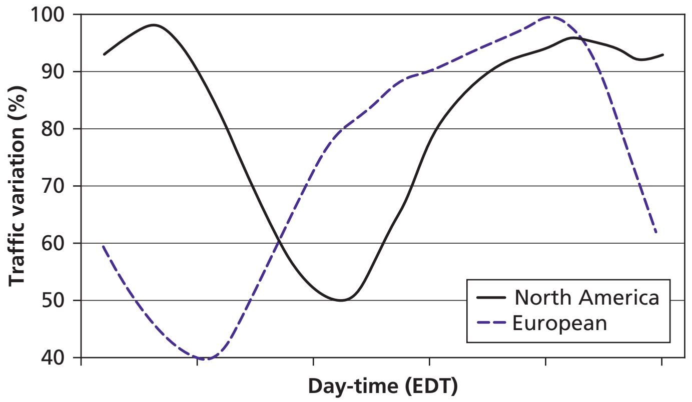
Diverse industrial/academic projects and initiatives have appeared over the last few years designed to reduce the power used by network equipment while also improving its performance [10]. Among them, we note the two main activities where Alcatel-Lucent contributes: the ECONET project and GreenTouch initiative. Energy COnsumption NETworks (ECONET) [17] is an integrated project (IP) funded by the European Commission, whose goals are to introduce novel network-specific paradigms and concepts enabling the reduction of energy requirements for wired network equipment by 50 percent in the short- to mid-term (and by 80 percent in the long run) with respect to the business-as-usual scenario. The GreenTouch [19] initiative, promoted by Alcatel-Lucent, aims at mastering the technologies for future green networks and proposing a long-term network infrastructure allowing a 1000x-reduction in overall energy consumption with respect to the current situation.

In this paper we focus on one aspect of energy aware networking that relates the definition of different power states for optical systems, the topic of a GreenTouch project called Highly Adaptive Layer for Meshed On-Off Optical Networks (HALF-MOON) [20]. The rest of the paper is organized as follows. We present a concept for traffic-aware networking and an overview of the work presented in the literature. Next, we introduce the traffic-aware strategy proposed within the HALF-MOON project, and present a power consumption model for optoelectronic devices along with the proposed control plane protocol extensions. We then present a case study, where a new problem formulation is described and the advantages of the proposed strategies are shown. We report on ongoing activities in standardization bodies on future energy-efficient optical networks. Finally, we offer our conclusions.

Traffic-Aware Networking

As a first step towards improving energy efficiency in optical networks, we analyzed traffic trends and consumer behavior. Research showed that traffic grows exponentially [26] and presents predictable variations [27] (e.g., daily, weekly), as depicted in **Figure 2**. On the contrary, optical networks are quasi-static systems in which all network elements have been over-provisioned/powered for peak traffic loads, regardless of the capacity actually being transported. Driving energy efficiency at the optical layer presents an optimal way to increase overall energy efficiency.

In a network designed to support the worst-case peak traffic, “traffic-aware” networking refers to network management techniques which allow both the Internet Protocol (IP) and Wavelength Division



EDT—Eastern Daylight Time

Figure 2.
Example of periodic traffic variations of traffic volume in European and North American networks.

Multiplexing (WDM) layers to consume energy according to client demands [34]. The energy savings introduced by "traffic-aware" networking are:

$$\rho = (P_{up} - \overline{P})/P_{up} \tag{1}$$

where P_{up} is the power required to transport the peak traffic and $\overline{P}$ is the daily average power.

A first step to drive energy consumption proportional to the actual transported traffic consists of powering optical systems/devices on the basis of traffic. To achieve this at the IP and WDM layers, various researchers have proposed a sleep-mode (low power consumption mode) state for optical systems [7]. Specifically, optical systems eligible for sleep-mode have been optoelectronic (OE) devices [33] and amplifier sites [9] because they contribute to energy consumption mainly at the optical layer [19].

Thanks to the introduction of sleep-mode, it is now possible to quantify the energy savings that "traffic-aware" networking could provide. Assuming that power consumption depends linearly on the carried traffic, and that residual power (P_{down}) is still consumed in absence of traffic, we have $P(T) = P_{down} + KT$. The power at peak traffic (T_{peak}) is P_{up}, so $K = (P_{up} - P_{down})/T_{peak}$ depends on the ratio between the up/down power [28]. Denoting T_{total} and $\overline{T}$ the total and average traffic at the considered timeframe (t_F), respectively, we can obtain from equation 1 that:

$$\begin{aligned}
\overline{\rho} &= 1 - \frac{\dfrac{\int_{t_F} P(t)dt}{\int_{t_F} T(t)dt}}{P_{up}} = 1 - \frac{\dfrac{\int_{t_F}[P_{down} + K \cdot T(t)]dt}{T_{total}}}{P_{up}} \\
&= 1 - \frac{P_{down} + \dfrac{P_{up} - P_{down}}{T_{peak}} \cdot \dfrac{\int_{t_F} T(t)dt}{T_{total}}}{P_{up}} \\
&= 1 - \frac{P_{down} + \dfrac{P_{up} - P_{down}}{T_{peak}} \overline{T}}{P_{up}} \\
&= \frac{P_{peak} - P_{down}}{P_{up}} \cdot \left|1 - \frac{\overline{T}}{T_{peak}}\right|
\end{aligned} \tag{2}$$

Where ρ' represents the energy savings provided by ideal "traffic-aware" networking; the closer ρ is to ρ' is, the higher the energy-efficiency.

To make energy consumption in the optical network more proportional to the carried traffic, two main approaches have been identified: those exploiting elastic optoelectronic devices [38], and those allowing the OE devices to enter a sleep-mode. We will focus on the latter approach.

Overview of Traffic-Aware Networking

An optical system can be switched-off if a) it is totally unused, or b) the traffic flowing through it remains under a given threshold, with residual traffic rerouting provided by the upper layers (multilayer networking [29]), in order to avoid traffic disruptions. Unfortunately, most of the elements in a core network cannot just be shut-down without affecting overall network performance. Until now, most published studies estimated energy savings based on the possibility of switching-off nodes and links. For example, a mixed integer linear program (MILP) formulation of this problem was provided in [18], while heuristics were proposed in [21]. [40] proposed a scheme to shut down idle line cards (and the corresponding optical circuit or lightpath) when the traffic load is low in IP-over-WDM networks. In this scheme, the physical topology is not changed and energy is saved by changing the virtual connectivity. Similarly, in [38] the authors proposed a scheme to save energy by shutting-down idle line cards, and also the chassis of IP routers when traffic decreases. To do so, further protocol enhancements around grooming procedures have to be proposed so as to reroute traffic at the upper layer. In [9] energy gain estimations are provided when optical links are switched-down; the work presented both centralized and distributed strategies to dynamically select the WDM links to be set in sleep-mode. The main drawback of this strategy is the impact on the robustness of the network against link failures (lower node connectivity), as well as the possibility of switching off links only when no lightpath traverses them, which means the strategy is only feasible under low traffic periods; it also requires dynamic lightpath reconfiguration capabilities in order to achieve appreciable benefits in most cases. [22] investigates the energy benefits of file transfers over rate-adaptive optical networks. The authors show analytically and by numerical simulations that the combination of rate-adaptation and the possibility of tuning the power of optoelectronic devices can reduce the per-bit energy by as much as 90 percent. Moreover they demonstrated that transition times related to setting-up devices or taking them down increased the file transfer latency.

HALF-MOON Approach

With the aim of saving energy, the HALF-MOON project proposed the dynamic power management of OE devices (i.e., transponders (TSPs) and regenerators (REGs)) [32]. OE devices can be totally or partially powered ("up" and "idle" states, respectively) or switched-off ("down" state). **Figure 3** shows the associated power states and transitions between them.

In the up-state, devices are fully powered and operational, whereas in down-state they are unpowered and unused. At the intermediate idle-state the device is non-operational but semi-powered, hence it does not transmit any traffic but is ready to do so on short notice. We suppose that the transition delay from idle to up is comparable to the delays required for the connection set-up (protocol forwards and optical switching), i.e., a few tens of milliseconds [33]. The idle-state is introduced to allow thermal stabilization of critical components (e.g., laser).

Power Consumption Model

A schematic of the OE devices we considered is represented in **Figure 4**. A transponder receives data from the client side and encodes it on a wavelength in the optical domain after suitable framing and the addition of a forward error correction (FEC) overhead. Given that the traffic is bi-directional, so are the transponders, and symmetric operations are guaranteed from the WDM optical domain to the client side. Whenever the signal becomes too degraded to transparently reach the destination, regenerators receive the optical signals and re-emit it after FEC. To estimate the power consumption of these OE devices, we considered 100 Gb/s signals with polarization-multiplexed quadrature phase shift keying (QPSK) modulation. Their description is reported in [33] and their relative power consumption is reported in **Figure 5** [11].

Control Plane Protocol Extension for Supporting OE Device Sleep-Mode

Adapting power consumption to the actual traffic requires dynamic management of the power state of the OE devices. This management can be

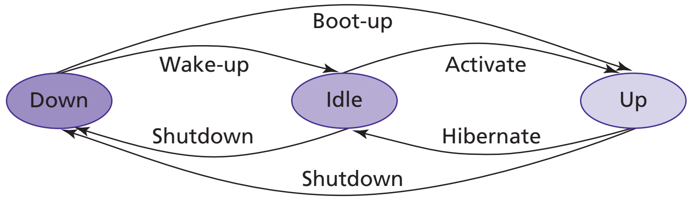
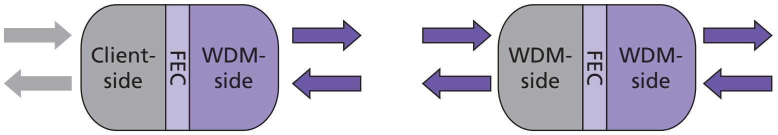


Figure 3.
Power-states relative to an optoelectronic device and transitions between such states.



(a) Add/drop transponder **(b)** Regenerator (2 half-transponders)

FEC—Forward error correction
WDM—Wavelength Division Multiplexing

Figure 4.
Schematic of the considered bi-directional optoelectronic devices.

	Component	Unit	TSP	REG	Power dissipation (W)	Powered at *idle*-state
Client side	Client-card	10	•		3.5	
	Framer	1	•		25	
FEC	FEC	1	•	• (x2)	7	
E/O modulation	Drivers	4	•	• (x2)	9	
	Laser (on-off)	1	•	• (x2)	6.6	•
O/E receiver	Local oscillator	1	•	• (x2)	6.6	•
	Photodiode + TIA	4	•	• (x2)	0.4	•
	ADC	4	•	• (x2)	2	
	DSP	1	•	• (x2)	100	
FEC	FEC	1	•	• (x2)	7	
Client side	Deframer	1	•		25	
	Client-card	10	•		3.5	
	Management power		•	•	+20% total power	•
	Total power		**351W**	**414W**		**18W TSP 36W REG**

ADC—Analog-to-digital converter
DSP—Digital signal processor
E/O—Electro-optical
FEC—Forward error correction
O/E—Optoelectronic
REG—Regenerator
TIA—Transimpedance amplifier
TSP—Transponder

Figure 5.
List of the typical components required for the reference 100 Gb/s optoelectronic devices, with their respective power consumption and components powered-up when the device is idle.

performed by the network control plane. However, current control plane solutions, such as the Generalized Multiprotocol Label Switching (GMPLS) protocol set [30], assume that network nodes and links are always operational (i.e., in th up-state). Therefore, by introducing different power states, the control plane architecture and protocols must be properly extended to enable dynamic power state transitions, without affecting network performance specifications imposed by the supported applications (e.g., reduced set-up time and recovery time). Standards bodies are already actively defining standards related to energy-efficient networks, as we will cover in a subsequent section. Additionally, some studies, such as [9], have proposed control plane-based approaches for reducing overall network power consumption. There, the authors propose centralized and distributed strategies to dynamically select the WDM links to be set to sleep-mode by aggregating active optical connections on only a few links. However, while some power savings can be achieved for low-traffic loads, setting links at sleep-mode impacts the robustness of the network against link failures, since it decreases network connectivity. Moreover, the proposed approaches require rerouting of all supported optical connections when a link power status is changed (using make-before-break strategies, not always available in today's optical networks), which requires additional routing and signaling actions and, eventually, more complexity at the GMPLS network control plane.

By comparison, the HALF-MOON approach relies on putting OE devices in sleep-mode while keeping links (optical amplifiers) always fully operational (up-state) in order to maintain unaltered network connectivity. "Traffic-aware" networking relies on the dynamic management of OE device power states, performed through properly extended GMPLS protocols. In current signaling protocols, i.e., Resource Reservation Protocol-Traffic Engineering (RSVP-TE) [1], the bit "A" in the ADMIN STATUS object of RSVP-TE path/resv messages [3, 4], is committed to administratively setting-up or taking down a specific lightpath or label-switched path (LSP). The network administrator can set the bit "A" to trigger specific actions to be taken locally at each network node crossed by the LSP. While "A" is set to 0, during normal network operation, the network device is powered and fully operational. By setting bit "A" to 1, a change to an un-operational and switched-off device state can be triggered; this is usually done in case of failures. A scheme of the "A" bit meaning is shown in **Table I**.

In HALF-MOON we propose to extend the signaling protocol to dynamically allow the management of a device's power state. To represent the different OE device power states (up, idle, and down), we propose a new bit "S," in addition to bit "A." In this manner, when A = 0, S is used to discriminate whether the OE devices are up or idle. Conversely, if A = 1, S discriminates between down-state and damaged, as indicated in **Table II.** Upon the reception of the RSVP-TE path/resv messages, the proper power state is triggered locally, according to the A and S bits.

Table I. Proposed bits in the signaling protocol for describing the OE device state.

	Current bit indicating OE device status
Proposed power states	**A**
Up-state	0
Idle-state	–
Down-state	–
Damaged	1

OE—Optoelectronic

Table II. Current bit in the signaling protocol for describing the OE device state.

	Proposed bit indicating OE device status	
Proposed power states	**A**	**S**
Up-state	0	0
Idle-state	0	1
Down-state	1	0
Damaged	1	1

OE—Optoelectronic

HALF-MOON Approach for Energy Savings: A Case Study

This section quantitatively evaluates the energy savings possible if operators adopt OE device sleep-mode (hereafter OESM) in their network devices. Furthermore, we benchmark the performance of OESM against the link sleep-mode (hereafter LSM) [9], where the links (i.e., amplifiers) can be switched-off. To complete the comparison, we also consider a scenario where both OE devices and link sleep-mode approaches are implemented, referred to as hybrid sleep-mode (hereafter HSM).

We propose a new MILP formulation to perform a translucent optical network planning while minimizing overall network energy consumption. This formulation jointly solves the routing, wavelength assignment (RWA), and regenerator placement problems for the offered peak traffic demands, while minimizing the total network power consumption arising from the required TSPs and REGs in optical nodes and amplifiers in optical fiber links. On the basis of the resulting translucent optical network design for the peak traffic load, the same formulation with additional constraints provides the energy savings that can be achieved with LSM, OESM, and HSM during low-traffic periods, by switching-off unused TSPs/REGs (in OESM and HSM) and links (in LSM and HSM) as possible. Such constraints force the use of already deployed OE devices when low-traffic is routed, avoiding the deployment of further resources and guaranteeing both an energy and cost-efficient network solution.

Two optical layer scenarios are considered and the performance of LSM, OESM, and HSM are evaluated over them. Specifically, we contemplate either a static or a reconfigurable optical layer. In the static optical layer case, no reconfiguration of already established optical connections is allowed in low-traffic periods. Therefore, offered demands in low-traffic periods must be supported over a subset of the lightpaths to be established for the peak traffic load. In the reconfigurable optical layer case, full freedom of reconfiguring already established optical connections is allowed at low-traffic periods, with the goal of reducing network energy consumption as much as possible. Note that even though reconfiguration can yield superior energy savings, active optical connections may incur unacceptable disruptions, which should be avoided in real network scenarios. Conversely, the disruption of active connections is completely eliminated in the static optical layer.

Energy savings were calculated for unprotected and 1:1 protected traffic scenarios. In the unprotected case, only one connection is associated to each demand, while in the 1:1 protected case, two optical paths are associated to each demand, namely, a working path over which the signal is sent, and a protection path where resources are reserved for future use in the event of a working path failure. In this study we suppose that OE devices are dedicated to the working and protection paths, meaning that if sleep-mode is not implemented such devices have to be powered on, even if useless.

Problem Formulation

We used a connectivity graph (CG) [39] technique for problem formulation, fixing the transparent reach of the optical signals to 1200 km, as suggested for 100 Gb/s coherent polarization division multiplexing (PDM)-QPSK in [33]. Node pairs are connected by logical links when a feasible transparent connection (without regenerators in the middle) exists between them in the optical layer. For the power consumption of the network elements, we assume that 100 Gb/s TSPs/REGs consume 350W to 420W in the up-state, whereas their consumption falls to 18W to 36W in idle-state [33]. Regarding the bidirectional optical amplifier sites, we assume they consume 290W, based on Alcatel-Lucent products [19]. These sites contain two erbium doped fiber amplifier (EDFA)-modules on a shelf (one per direction), a monitoring system, power supply, and fans. TSPs/REGs can be switched-off in low-traffic periods if not supporting any active lightpath, while a bidirectional amplifier box can only be switched-off if not operating in any direction. In this study, we assume that TSPs/REGs and optical amplifiers consume a negligible amount of power when they are switched-off. The input parameters and decision variables for our problem formulation are as follows:

Input parameters:

G(N,E): Physical network topology; *N*: Set of physical nodes; *E*: Set of unidirectional fiber links.

W: Number of wavelengths per fiber link.

$G'(N,E')$: Network CG; N: Set of physical nodes; E': Set of logical links.

P: Set of feasible paths over $G(N,E)$ according to the maximum transparent reach of the signal.

$P_{e'}$: Set of feasible paths over $G(N,E)$ that can be used to allocate traffic routed over $e' \in E'$.

D: Set of unidirectional 1:1 protected demands offered to the network.

K: Set of possible lightpath modes, $K = \{working, protection\}$.

E_t^k: Energy consumption of a TSP supporting a lightpath in mode k.

E_r^k: Energy consumption of a REG supporting a lightpath in mode k.

E_a: Energy consumption of a bidirectional optical amplifier box.

E_e: Energy consumption of fiber link $e \in E$; $E_e = 0.5 * (ceil\ (D_e / D_{ia} + 1) + 2)\ E_a$, where D_e is the physical distance of $e \in E$ (in km) and D_{ia} is the inter-amplifier distance (in km), typically 80 km.

$z_e' \in \{0,1\}$: 1 if $e \in E$ supports at least 1 lightpath of the peak traffic; 0 otherwise.

$n_t^{k}{}'(n)$: Number of TSPs at node $n \in N$ supporting lightpaths in mode k for the peak traffic.

$n_r^{k}{}'(n)$: Number of REGs at node $n \in N$ supporting lightpaths in mode k for the peak traffic.

$\pi_{pw}' \in \{0,1\}$: 1 if wavelength w is used in $p \in P$ for the peak traffic; 0 otherwise.

C: A very large constant.

ε: A very small constant.

<u>Decision variables:</u>

$x^k_{de'} \in \{0,1\}$: 1 if a lightpath in mode $k \in K$ of $d \in D$ is routed on logical link $e' \in E'$; 0 otherwise.

$y^k_{dpw} \in \{0,1\}$: 1 if a lightpath in mode $k \in K$ of $d \in D$ is supported on the transparent optical path $p \in P$ with wavelength w; 0 otherwise.

$z_e \in \{0,1\}$: 1 if $e \in E$ supports at least 1 lightpath; 0 otherwise.

$n_t^k(n)$: Number of TSPs used by lightpaths in mode k at node $n \in N$.

$n_r^k(n)$: Number of REGs used by lightpaths in mode k at node $n \in N$.

Objective function equations and additional constraints for each scenario follow below.

Model Formulation

$$\min \sum_{n}\sum_{k}\left(E_t^k n_t^k(n) + E_t^k n_t^k(n)\right) + \sum_{e} E_e z_e + \varepsilon \sum_{p}\sum_{w} w\pi_{pw} \tag{3}$$

subject to:

$$\sum_{e' \in \delta^+(n)} x^k_{de'} - \sum_{e' \in \delta^+(n)} x^k_{de'} = \begin{cases} 1 \text{ if } n = a(d) \\ -1 \text{ if } n = b(d) \quad \forall d \in D,\ k \in K,\ n \in N. \\ 0 \text{ otherwise} \end{cases} \tag{4}$$

$$\sum_{p \in p_{e'}}\sum_{w} y^k_{dpw} = x^k_{de'},\ e' \in E',\ d \in D,\ k \in K. \tag{5}$$

$$\sum_{d}\sum_{p \in p: e \in p}\sum_{k} y^k_{dpw} \leq 1 \quad \forall\, e \in E,\ w \in \{1, \ldots \mathrm{W}\}. \tag{6}$$

$$\sum_{p \in p: e \in p}\sum_{w}\sum_{k} y^k_{dpw} \leq 1 \quad \forall\, d \in D,\ e \in E. \tag{7}$$

$$\sum_{d}\sum_{p \in p: \langle e \rangle \in p}\sum_{w}\sum_{k} y^k_{dpw} \leq C z_e \quad \forall\, e \in E. \tag{8}$$

$$\sum_{d \in D: n = a(d) \vee n = b(d)} 1 \leq n_t^k(n) \quad \forall\, n \in N,\ k \in K. \tag{9}$$

$$\sum_{e' \in \delta^-(n)}\ \sum_{d \in D\ n \neq b(d)} x^k_{de'} \leq n_r^k(n) \quad \forall\, n \in N,\ k \in K. \tag{10}$$

$$\sum_{d}\sum_{k} y^k_{dpw} \leq \pi_{pw} \quad \forall\, p \in P,\ w \in \{1, \ldots W\}. \tag{11}$$

Additional constraints for LSM:

$$n_t^k = n_t^{k}{}'(n) \quad \forall\, n \in N,\ k \in K. \tag{12}$$

$$n_r^k = n_r^{k}{}'(n) \quad \forall\, n \in N,\ k \in K. \tag{13}$$

Additional constraints for OESM:

$$\sum_{k} n_t^k(n) \leq \sum_{k} n_t^{k}{}'(n) \quad \forall\, n \in N. \tag{14}$$

$$\sum_{k} n_r^k(n) \leq \sum_{k} n_t^{k}{}'(n) \quad \forall\, n \in N. \tag{15}$$

$$z_e = z_e' \quad \forall\, e \in E. \tag{16}$$

Additional constraints for HSM:

$$\sum_{k} n_t^k(n) \leq \sum_{k} n_t^{k}{}'(n) \quad \forall\, n \in N. \tag{17}$$

$$\sum_{k} n_r^k(n) \leq \sum_{k} n_t^{k}{}'(n) \quad \forall\, n \in N. \tag{18}$$

Additional constraints for static optical layer:

$$\pi_{pw} \leq \pi_{pw}' \quad \forall\, p \in P,\ w \in \{1, \ldots W\}. \tag{19}$$

Objective function equation 3 with constraints equations 4 through 11 are used to optimally design a green translucent optical network satisfying the peak traffic load. The third term in equation 3 together with constraints equation 11 is used to store path-wavelength utilization and foster model convergence. Constraints equation 4 details the flow conservation constraints, which also ensure that all demands are served. Notation *a(d)* and *b(d)* is used to refer to the source and destination nodes of demand $d \in D$. For the 1:1 protection scenario, for each demand we associate one working and one protection connection. Constraints equation 5 ensures that lightpaths routed over *G′(N,E′)* are allocated over *G(N,E)*. Constraints equation 6 represents the wavelength clashing constraints, ensuring that any wavelength can support one lightpath at most. Constraints equation 7 ensures link disjointness between working and backup lightpaths of a demand. Constraints equation 8 is used to account for link usage in the network. Notation $<\mathbf{e}>$ denotes link $\mathbf{e} \in \mathbf{E}$ or the one in the reverse direction, so as to ensure that amplifiers in a link are only switched-off if not supporting lightpaths in any direction, because of the bidirectional amplifier operation mode. Constraints equations 9 through 11 are used to account for link, transponder, regenerator and path-wavelength utilization.

For low-traffic periods, a subset of peak traffic connections is maintained by including some of the constraints from equations 12 through 19, depending on the evaluated energy-aware approach and particular optical layer capabilities. For LSM we force all OE devices dimensioned for the peak traffic load to remain in up-state during low-traffic periods, even if not needed. Conversely, for OESM, all fiber links must always remain active. In HSM, both unused TSPs/REGs and optical amplifiers can be switched-off when not in use. As mentioned previously, constraints equation 19 ensures that for the static optical layer case, the lightpaths in low traffic periods must be a subset of those established for the peak traffic scenario. There is no such restriction when the optical layer is reconfigurable.

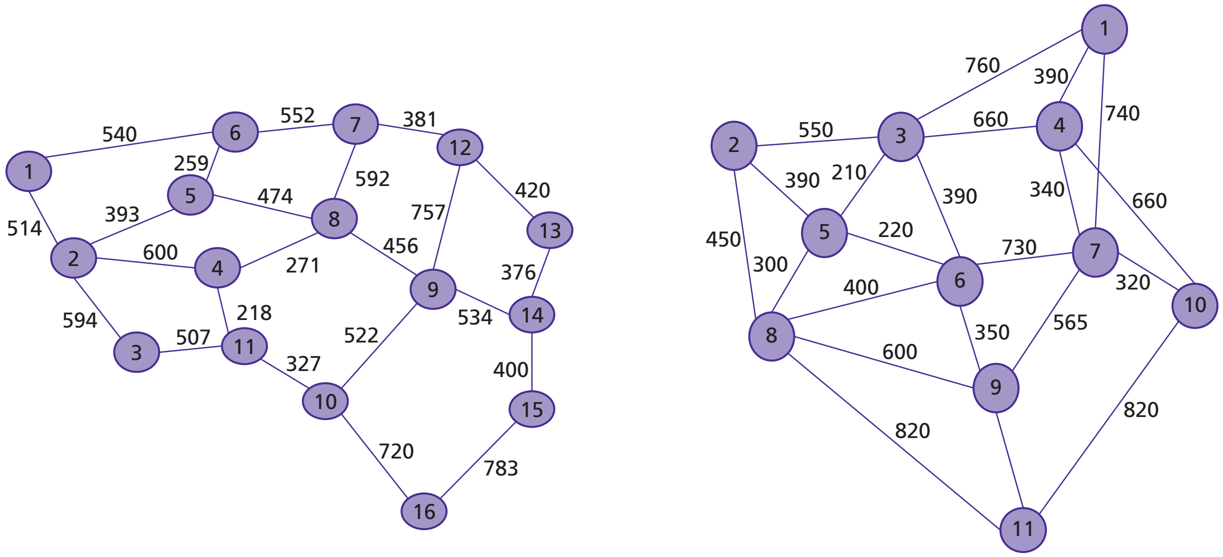
Even though the formulation above accounts for 1:1 protected demands, it can easily be adjusted to match unprotected network scenarios. In this case, the set of parameters *K*, representing the working and protection paths, is reduced to only one element: *{working}*. Moreover, constraints equation 7 which ensures link disjointness between a demand's working and backup paths is unnecessary in the unprotected case and can be removed.

Hypotheses and Results

We compared the performance of LSM, OESM, and HSM in two different Pan-European network topologies namely the European Optical Network (EON) [33] and the COST 239 Network [2], as shown in **Figure 6**. Characteristics of both are summarized in Figure 6. We assume 16 bidirectional wavelengths for the EON and 10 bidirectional wavelengths for the COST 239 network, per link at 100 Gb/s. Regarding the traffic characteristics, in the peak traffic scenario, we generate a set of demands between randomly chosen source-destination pairs. The size of this set is large enough to fill the network, avoiding blocking. The number of requests routed in the unprotected scenario is almost twice the number of requests routed in the protected case since in the latter, two paths are associated with one request. Given the network scenario, the same peak-demand set is used for all the energy planning performed with the different traffic-aware approaches. For low traffic periods, we selected a percentage of the peak traffic demands randomly and disconnected the remainder. We launched 20 independent model executions per traffic load, each time with a new random demand selection, and we averaged the results presented in **Table III** and **Table IV**.

In the scenario considering 1:1 protection, if OESM is implemented, TSPs/REGs allocated for backup paths can be set in idle-state to save energy when inactive, while still ensuring fast response times in case of failure (i.e., gold class setup times average ~10 milliseconds [32]). Regarding amplifier sites, however, even if they could be woken-up in tens or hundreds of milliseconds, long-haul links easily comprise many which have to be sequentially activated. This would result in a total link wake-up time of seconds, which is prohibitive for recovery. Hence, even network links supporting only backup connections must continuously remain in the up-state.

Therefore, in OESM and HSM, E_t^k and E_r^k are set to 350W and 420W for $k = working$, whereas they equal 18W and 36W for $k = backup$. Conversely, they remain fixed at 350W and 420W both for $k = working$



Number of nodes	16
Number of links	23
Average node degree	2.88
Average link length (km)	487

(a) 16-node European Optical Network (EON)

Number of nodes	11
Number of links	22
Average node degree	4
Average link length (km)	421

(b) COST 239 small network

COST—European Cooperation in the field of Scientific and Technical Research
EON—European Optical Network

Figure 6.
Network topologies for the EON and COST-239 networks.

and $k = backup$ in LSM, since no OE device power management is available in this approach.

Table III and Table IV show the energy consumption achieved by LSM, OESM, and HSM in both networks in a static versus reconfigurable optical layer, assuming unprotected and 1:1 protection scenarios. Results were obtained using IBM's CPLEX* v12.2 solver, setting the optimality gap parameter to one percent.

Results from Table III and Table IV show that the consumption observed for both the unprotected and 1:1 protected scenarios behaves in the same manner, even if the unprotected case performs slightly better because there is no disjointedness condition between paths. In the unprotected case, at peak traffic the power is the same for all three strategies since the same number of OE devices are fully powered. We also noted that for the EON network, implementing the path reconfigurations did not result in further power savings. In the 1:1 protected case, we saw improvements of up to two percent and three percent respectively for the LSM and HSM strategies, while improvements in the unprotected case reach four percent in both cases. The OESM strategy gains no advantage from the reconfigurations because savings are driven only from the possibility of skipping intermediate regenerators. On the other hand, reconfiguration capabilities provided more savings for the COST 239 network: up to five percent for LSM, and 14 percent for the HSM strategy respectively, for both protected and unprotected cases. These higher savings are mainly due to the high network connectivity. Indeed with the increase in network connectivity, the number of paths reaching the destination node also increases and it is easier to concentrate traffic along only a few links, switching-off amplifiers.

Table III. Network power consumption (kW) for the unprotected demands.

		STATIC optical layer case							RECONFIGURABLE optical layer case					
Scenario		Link sleep-mode		OE device sleep-mode		Hybrid sleep-mode			Link sleep-mode		OE device sleep-mode		Hybrid sleep-mode	
Network	Load (%)	P(AMP-TSP-REG)	Total	P(AMP-TSP-REG)	Total	P(AMP-TXP-REG)	Total		P(AMP-TSP-REG)	Total	P(AMP-TSP-REG)	Total	P(AMP-TSP-REG)	Total
EON	100	47.56-140-41.58	229.14	47.56-140-41.58	229.14	47.56-140-41.58	229.14		47.56-140-41.58	229.14	47.56-140-41.58	229.14	47.56-140-41.58	229.14
	70	46.63-140-41.58	228.21	47.56-98-29.27	174.83	46.28-98-30.45	174.73		38.11-140-41.58	219.69	47.56-98-28.62	174.18	38.73-98-31.4	168.12
	50	39.77-140-41.58	221.35	47.56-70-20.85	138.41	40.56-70-24.09	134.64		33.12-140-41.58	214.70	47.56-70-20.2	137.76	35.47-70-23.31	128.78
	30	34.1-140-41.58	215.68	47.56-42-12.56	102.12	35.87-42-16.34	94.21		27.24-140-41.58	208.82	47.56-42-12.03	101.59	30.70-42-17.20	89.90
	10	27.5-140-41.58	209.09	47.56-14-4.24	65.80	28.54-14-6.80	49.34		25.37-140-41.58	206.95	47.56-14-4.07	65.63	28.13-14-15.42	47.55
COST 239	100	41.47-129.5-16.8	187.78	41.47-129.5-16.8	187.78	41.47-129.5-16.8	187.78		41.47-129.5-16.8	187.78	41.47-129.5-16.8	187.78	41.47-129.5-16.8	187.78
	70	41.23-129.5-16.8	187.53	41.47-91-10.96	143.43	40.24-91-11.13	142.37		35.24-129.5-16.8	181.54	41.47-91-10.42	142.89	35.67-91-11.13	137.80
	50	37.05-129.5-16.8	183.35	41.47-65.1-7.37	113.94	38.06-65.1-8.40	111.56		27.96-129.5-16.8	174.26	41.47-65.1-7.29	113.86	27.34-65.1-8.67	101.12
	30	29.52-129.5-16.8	175.82	41.47-39.2-4.7	85.37	29.68-39.2-8.13	77.01		20.56-129.5-16.8	166.86	41.47-39.2-4.58	85.25	19.87-39.2-6.70	65.76
	10	19.15-129.5-16.8	165.45	41.47-13.3-1.51	56.28	19.73-13.3-4.67	37.70		16.23-129.5-16.8	162.53	41.47-13.3-1.5	56.27	16.65-13.3-3.11	33.05

Table IV. Network power consumption (kW) for 1:1 protection scenario.

		STATIC optical layer case						RECONFIGURABLE optical layer case					
Scenario		**Link sleep-mode**		**OE device sleep-mode**		**Hybrid sleep-mode**		**Link sleep-mode**		**OE device sleep-mode**		**Hybrid sleep-mode**	
Network	**Load (%)**	**P(AMP-TXP-REG)**	**Total**	**P(AMP-TXP-REG)**	**Total**	**P(AMP-TXP-REG)**	**Total**	**P(AMP-TXP-REG)**	**Total**	**P(AMP-TXP-REG)**	**Total**	**P(AMP-TXP-REG)**	**Total**
EON	100	49.88-117.6-58.8	226.28	47.27-61.82-20.76	129.85	47.27-61.82-20.76	129.85	49.88-117.6-58.8	226.28	47.27-61.82-20.76	129.85	47.27-61.82-20.76	129.85
	70	47.53-117.6-58.8	223.93	47.27-43.42-14.47	105.16	47.20-43.42-14.57	105.19	42.79-117.6-58.8	219.19	47.27-43.42-14.17	104.86	42.50-43.42-16.47	102.39
	50	45.28-117.6-58.8	221.68	47.27-30.91-10.42	88.60	43.92-30.91-11.75	86.58	40.89-117.6-58.8	217.29	47.27-30.91-10.36	88.54	40.34-30.91-12.22	83.47
	30	40.9-117.6-58.8	217.30	47.27-18.40-6.27	71.94	39.11-18.40-8.46	65.97	37.40-117.6-58.8	213.81	47.27-18.40-6.00	71.67	37.67-18.40-8.72	64.79
	10	33.35-117.6-58.8	209.75	47.27-5.89-1.92	55.08	31.04-5.89-3.32	40.25	29.70-117.6-58.8	206.10	47.27-5.89-1.90	55.06	30.41-5.89-3.07	39.36
COST 239	100	47.27-112-18.9	178.17	46.98-58.88-5.88	111.74	46.98-58.88-6.37	112.23	47.27-112-18.9	178.17	46.98-58.88-5.88	111.74	46.98-58.88-6.37	112.23
	70	46.56-112-18.9	177.46	46.98-41.22-4.06	92.26	45.95-41.22-4.31	91.48	38.95-112-18.9	169.85	46.98-41.22-4.01	92.21	37.75-41.22-4.67	83.64
	50	42.09-112-18.9	172.99	46.98-29.44-2.79	79.21	40.54-29.44-3.53	73.51	32.68-112-18.9	163.58	46.98-29.44-2.76	79.18	32.19-29.44-4.16	65.79
	30	35.08-112-18.9	165.98	46.98-17.66-1.83	66.48	34.74-17.66-3.07	55.48	27.19-112-18.9	158.09	46.98-17.66-1.81	66.45	25.95-17.66-3.44	47.06
	10	24.10-112-18.9	155.00	46.98-5.89-0.50	53.37	23.10-5.89-1.53	30.52	20.3-112.18.9	151.20	46.98-5.89-0.50	53.37	20.59-5.88-1.13	27.61

AMP—Amplifiers
COST—European Cooperation in the field of Scientific and Technical Research
EON—European Optical Network
OE—Optoelectronic
P—Power
REG—Regenerator
TSP—Transponder

Now, to estimate how these different approaches improve the daily power efficiency at the optical layer, we considered the traffic variations reported in Figure 2 and computed the power consumption for each traffic load by considering the results reported in Table III and Table IV. The different loads are computed assuming a step function profile with static traffic at each time interval. At each step we assumed a five percent traffic variation with respect to peak traffic.

In **Figure 7** shows the daily power consumption for both the EON and the COST 239 networks across all considered traffic-aware strategies; unprotected and protected dimensioning results are also reported. We also report the daily traffic behavior (dashed curves). As there are not many differences between the static and dynamic scenarios for HSM and OESM, we only reported results for the static case. As Figure 7 shows, the daily power consumption follows the traffic load for all four strategies; however, they can be differentiated based on how closely they track traffic load fluctuations. It appears that the introduction of LSM leads to hardly any power savings, while HSM outperforms OESM only at traffic loads lower than 60 percent. This means that implementing just OESM is enough to improve power efficiency without requiring many system power reconfigurations or requiring connection rerouting. Finally, to measure the efficiency of the proposed strategies, we compute the ρ factor (equation 1) relative to each strategy and ρ' (equation 2), indicating the maximum savings obtained in the case of ideal "traffic-aware" networking, equal to 25.60 percent for the traffic variations considered. These values are presented in **Table V.** Comparing the ρ values of all six strategies, we confirmed that link power management does not lead to meaningful savings; hence, we concluded that the tradeoff for achieving power efficient traffic-aware networking and easy network power management is only obtained with a static OESM strategy.

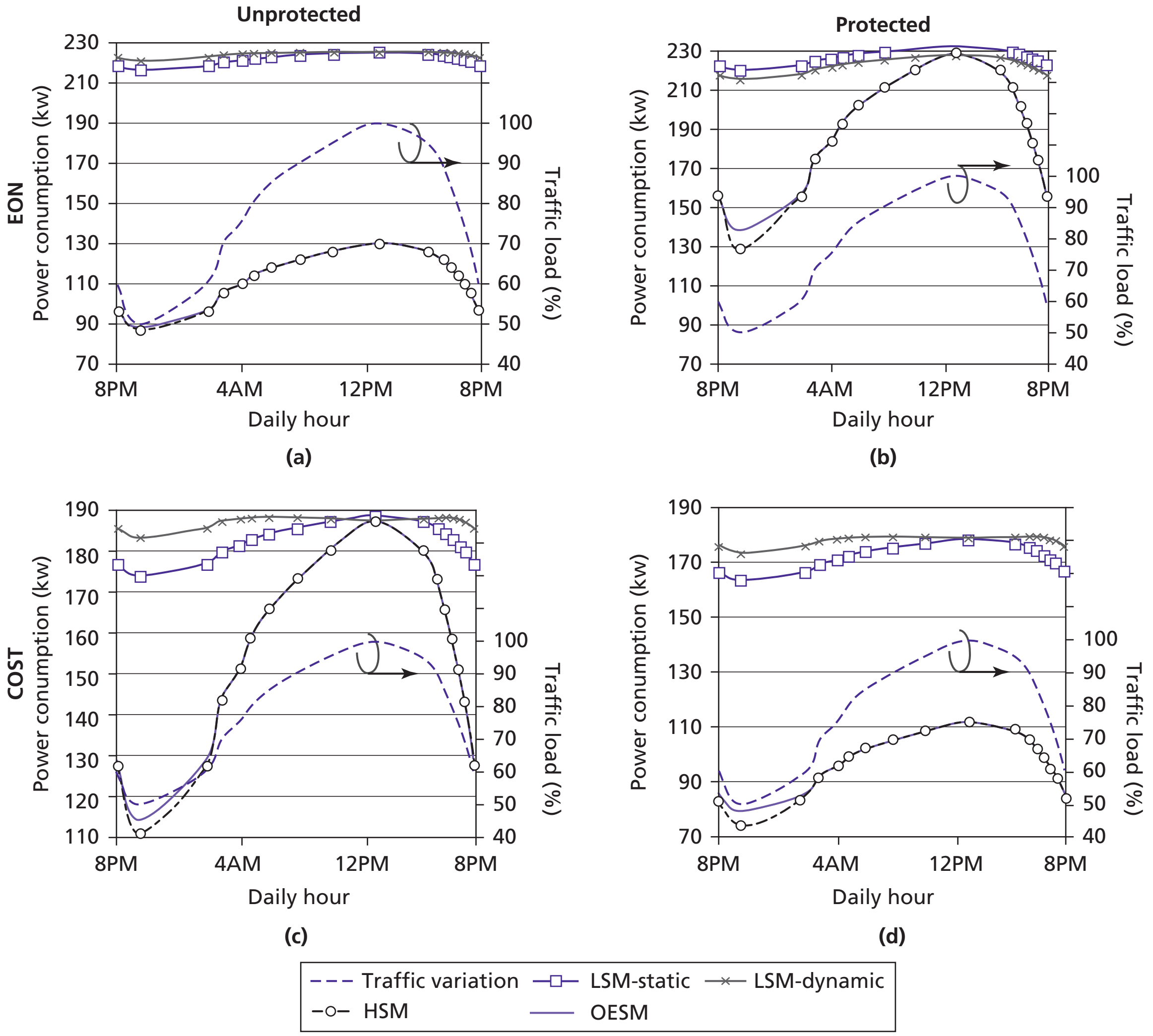
The gap between the theoretical values and those obtained via the traffic-aware schemes we proposed is due to the impossibility of adapting the power of all devices as a function of the traffic carried. Indeed some links remain powered even if only a few channels traverse them and the amplifier power cannot be adjusted as a function of the link load. This explanation is confirmed by observing the power saving improvements obtained when moving from the OESM to the HSM strategy.

Standards on Future Energy-Efficient Optical Networks

This section aims at providing a statement on green networking by describing work-in-progress within industrial initiatives and standards bodies. The activities towards standardization of energy-efficient technologies have been led by major players such as the European Telecommunications Standards Institute (ETSI), ITU Telecommunication Standardization Sector (ITU-T), Internet Engineering Task Force (IETF), and the Institute of Electrical and Electronics Engineers (IEEE), as reported and summarized in [6]. In the following we enhance this survey by citing the works that are more relevant in this context.

The Energy MANagement (EMAN) [25] working group at IETF is investigating leveraging existing standards such as those from the International Electrotechnical Commission (IEC), American National Standards Institute (ANSI), Distributed Management Task Force (DMTF) and others as much as possible. The EMAN defines requirements for the management of energy-aware network equipment by specifying the properties necessary for enabling network management, node controllers, and network devices to be energy aware. This applies to explicit energy aware requirements for extensions of the network control functions [36]; and also to specify functions to monitor and control the power state of network equipment to remotely control energy aware management systems [23].

More specifically, the EMAN working group has specified a framework for managing the power supply of devices within or connected to communication networks. The framework describes how to identify, classify, and provide context for equipment in a communications network from the point of view of energy management. In this context, the energy management domain is defined as a set of energy objects, for which each object is identified and classified. Energy objects are controlled and monitored considering their power,



COST—European Cooperation in the field of Scientific and Technical Research
EON—European Optical Network
HSM—Hybrid sleep-mode
LSM—Link sleep-mode
OE—Opto-electronic
OESM—OE-device sleep-mode

Figure 7.
Daily power consumption for the EON and COST networks as a function of the power strategy used.

power state, energy demand, power quality, and battery. The framework focuses on energy management and monitoring for IP-based network equipment such as routers, switches, personal computers (PCs), IP cameras, smartphones and other devices, and describes how energy information can be retrieved from IP-enabled devices using Simple Network Management Protocol (SNMP), and more specifically, management information bases (MIBs) for SNMP.

The approach used by the EMAN working group is to fundamentally enhance the existing functions of network management systems and related network protocols to be able to control, manage, and monitor power supplies of different devices. In such a context, the network management system (NMS) is also enabled to manage overall network energy efficiency, in addition to the typical network management functions, such as security management or

Table V. **ρ values relative to the different traffic-aware strategies as a function of the studied network and protection scenarios.**

ρ for EON (%)						
	LSM		OESM		HSM	
	Static	Dynamic	Static	Dynamic	Static	Dynamic
Unprotected	2.43	2.2	17.35	17.35	17.57	19.15
1:1 protected	0.53	1.59	14.02	14.02	13.8	14.94
ρ for COST 239 (%)						
	LSM		OESM		HSM	
	Static	Dynamic	Static	Dynamic	Static	Dynamic
Unprotected	0.38	3.41	17.03	17.03	17.26	20.12
1:1 protected	0.78	3.65	12.67	12.67	13.83	18.24

EON—European Optical Network
HSM—Hybrid sleep-mode
LSM—Link sleep-mode
OE—Optoelectronic
OESM—OE device sleep-mode

identity management. An energy management system (EnMS) is an NMS which exclusively manages energy on network devices. An EnMS may be limited to monitoring energy use, or it may also implement control functions [13]. The EMAN working group proposes to implement EnMS by extending existing SNMP support to the EMAN-specific MIBs. SNMP provides an industry-proven and well-known mechanism to discover, secure, measure, and control SNMP-enabled end devices. The EMAN framework provides an information and data model to unify access to a large range of devices.

On the other hand, IETF drafts addressing energy efficiency are continuously being submitted, although they are in early stages. [42] describes current activities related to energy efficiency being conducted by the IETF and Internet Research Task Force (IRTF) while also highlighting potential problems for realizing an energy-efficient Internet, such as proper operation of protocols and network resiliency. For example, the authors point out that some Internet protocols could be broken if sleep-modes were to be introduced because they operate based on the assumption that the participating nodes are always-on.

Specifically regarding GMPLS-controlled optical networks, [35] discusses some requirements of GMPLS protocol extensions for energy-efficient traffic engineering. The authors claim that extensions to the Open Shortest Path First (OSPF), Resource Reservation Protocol (RSVP), and Link Management Protocol (LMP) protocols are required to support Traffic Engineering (TE) link status (according to the power state of the corresponding network elements), LSP status (to differentiate between cases of link failure and link sleep), and link power on/off capability. [37] discusses some general requirements for an energy aware control plane for both wired and wireless networks.

In parallel with the standardization effort towards energy aware communication networks, tools and methodologies for benchmarking, measuring, and reporting on the energy efficiency and effectiveness of telecom services are being investigated. As an example, [10] proposes an energy rating system. A green service index rating is then calculated from the proposed energy rating system to enable service consumers to get useful information regarding the energy efficiency of their services. The green service index is also expected to enhance competition based on improved energy outcomes and to drive industry practice towards improving energy efficiency. An accepted and standardized energy rating system offers a potential means for governments and policy makers to address global greenhouse gas emission objectives and achieve better environmental outcomes.

Conclusions

The expected traffic growth will push both network operators and service providers towards the implementation of energy-efficient solutions for communications networks. Traffic-aware networking offers a promising approach for optical transport networks. It is enabled by introducing sleep-mode/idle-states for optical systems, guaranteeing very low energy consumption when systems are not operating (i.e., not supporting any traffic). In this paper we presented the HALF-MOON traffic-aware approach, where three power states related to optoelectronic (OE) devices are introduced. To efficiently adapt power consumption to actual traffic, we also introduced control plane extensions that will enable the dynamic management of the power state of such devices at network nodes. We proposed a mathematical formulation for estimating the energy consumption when the proposed OE device power management is implemented and we considered two traffic scenarios—one with no protection, and another with 1:1 protection. We compared this solution with a link sleep-mode strategy presented in the literature, and another solution which jointly employed OE device power management and link-sleep mode (hybrid case). Daily traffic variations were used for the comparison and the daily network power requirements estimated when the different traffic-aware strategies were implemented; savings were calculated by comparing such consumption with a case in which no power management was performed. Results showed that the standalone link-sleep mode improves power efficiency up to 3.5 percent, while OE device power management obtains up to 17 percent savings. Moreover, if both of these strategies were implemented jointly, power savings increased up to 20 percent The hybrid strategy does not strongly improve network efficiency and introduces more complexity, requiring many path and system reconfigurations. We thus can conclude that among all the traffic-aware networking scenarios we investigated, OE device power management offers the most promising strategy for more energy-efficient optical networks.

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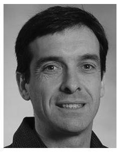
ANNALISA MOREA is a research engineer in the Optical Networks Department at Bell Labs' Centre de Villarceaux in Nozay, France. She graduated in telecommunication from Politecnico di Torino, Italy, and from École Nationale Supérieure des Télécommunications (ENST) Paris, France. She also received a Ph.D. degree in computer science and networks from ENST Paris, carrying out her work at the laboratories of France Telecom R&D in Lannion. Her thesis focused on optical network communication, particularly on the performance and interests of new translucent optical networks. Dr. Morea's research interests include optical network routing and dimensioning to improve and innovate transparent network solutions.

JORDI PERELLÓ is an assistant professor in the Computer Architecture Department (DAC) at the Universitat Politècnica de Catalunya (UPC), Spain. He received M.Sc. and Ph.D. degrees in telecommunications engineering from UPC. He has participated in various FP-6 and FP-7 European research projects including LIGHTNESS, EULER, STRONGEST, and DICONET. Dr. Perelló has published more than 50 articles in international journals, conference proceedings, and book chapters. His research interests concern resource management, quality of service issues, and survivability of next-generation optical transport networks.

SALVATORE SPADARO is an associate professor in the Optical Communications group within the Signal Theory and Communications Department at the Universitat Politècnica de Catalunya (UPC), Spain. He received the M.Sc. and the Ph.D. degrees in telecommunications engineering from UPC, as well as a Dr. Ing. degree in electrical engineering from Politecnico di Torino, Italy. He has been member of staff at UPC's the Advanced Broadband Communications Centre (CCABA) for the past 13 years. He has participated in various FP-6 and FP-7 European research projects including LIGHTNESS, EULER, STRONGEST, and DICONET. Dr. Spadaro has published more than 100 articles in international journals and conference proceedings. His research interests are in the fields of all-optical networks with emphasis on network control and management, resilience and network virtualization.



DOMINIQUE VERCHÈRE is a research engineer within the Networking and Networks research domain at Bell Labs' Centre de Villarceaux in Nozay, France. He holds a B.Sc. in electrical engineering, a B.Sc. in physics, and an M.Sc. in material physics from the University of Grenoble, and M.Sc. and Ph.D. degrees in computer science on performance evaluation from the University of Paris VI. His current research focus is on semantic and autonomic technologies. His tenure at Bell Labs has also included work on the design and development of router control software, data path processing, and terabit-switching capacity systems such as terabit IP optical routers; the development of resilience functions for optical cross-connects according to GMPLS based on RSVP-TE and OSPF-TE extensions; and on the control and management of carrier-grade Ethernet services. Dr. Verchere has participated in European projects including TBONES, NOBEL1 and NOBEL2, EuroNGI and CARRIOCAS. He has published more than 40 papers and 25 patents, and has been a member of Alcatel-Lucent Technical Academy since 2003.

MARTIN VIGOUREUX is a research manager at Bell Labs' Centre de Villarceaux in Nozay, France. In his current position, he manages research for distributed control, self-management and autonomic network architectures, from design to validation and demonstration by means of prototyping and simulation. He began his career at Alcatel after receiving an M.Sc. degree in high frequency electronics. His research is focused on advanced control architectures and protocols and their applicability to integrated systems and packet based networks. Mr. Vigoureux is active in both the ITU-T and IETF standardization bodies, is highly involved in the specification and standardization of the MPLS transport profile (MPLS-TP), and is MPLS Working Group Secretary at IETF. He is also a member of the IFIP Working Group on Smart Networks as part of the Technical Comity 6 (TC6). ◆