Modeling Energy Consumption in Next-Generation Wireless Access-over-WDM Networks with Hybrid Power Sources

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Abstract

Energy consumption is now one of the most important issues for network carriers, since the majority of the energy needed for their operation is consumed in the wireless access and optical transport networks. The continuous growth in the wireless customers and traffic volumes and the consequent energy demand on modern carriers' broadband infrastructures require reconsidering their energy efficiency, by starting from the formulation of new, more complete and representative network models that should become the foundations for modern energy-aware control plane architectures.

Accordingly, this work presents a novel comprehensive energy model for next-generation wireless access-over-optical-transport networks characterized by hybrid power systems (i.e., multiple dynamically available power sources). The objective is to identify the energy-related information that need to be handled at the control plane layer to support energy-aware networking practices. Such information can be made available to suitable energy-aware routing and wavelength assignment algorithms that may exploit them to optimize the overall network energy-consumption and reducing the associated carbon footprint. The proposed model may be taken as a reference for the implementation of new energy-aware control plane protocols (routing and signaling) that make use of power-related considerations to achieve energy-efficiency and energy-awareness in wavelength-routed network infrastructures.

Keywords: Mobile Access Networks, Energy Model, Next-Generation Networks, Energy-Awareness, Hybrid Power Source

1. Introduction

Nowadays, about 30% of worldwide primary energy is spent for producing electrical energy by using mainly "dirty" sources (e.g., burning oil, gas), and only a small share comes from "clean" renewable sources (e.g., sun, wind, tide, geothermal, etc.) [1]. It has also been estimated that the energy consumption of the whole ICT sector reaches about the 7% of the worldwide electricity production, the most part of which is due to large-scale telecommunication infrastructures and highly connected data centers.

In this scenario, where mobile Internet connectivity becomes the fastest growing business in the telecommunications market, due to the evolution of digital cellular, portable computing and personal communication technologies as long as to the convergence of mobile and fixed services, the wireless access network assumes a large role in both the global energy consumption and green house gases (GHG) production [2], [3].

On the other hand, due to the continuous increment in the number of mobile users (7 trillion wireless devices serving 7 billion users by 2017, according to a wireless world research forum forecast [4]) and their need for bandwidth/QoS guaranteed end-to-end communication services, the impact that mobile related traffic may have on the fixed optical transport infrastructure and its energy consumption is estimated to grow of about 12% per year [5].

These facts require new management strategies aiming at improving the energy efficiency of both broadband access and transport infrastructures by reducing the power demand associated to most of their fundamental operation activities. The main available options to achieve such an energy efficiency objective come from a combination of traffic engineering and environmental considerations. Traffic engineering practices have the final objective of minimizing the use of energy-hungry equipment within the transport network and limiting the impact of resource load on power consumption, by simultaneously maximizing the number of unused interfaces that can be put into low-power modes when inactive (to be immediately awakened ween needed). This has also an additional impact on GHG emissions that becomes more significant on the wireless access networks, that are known [4] to be responsible for roughly two-thirds of the total CO_2 emissions, and whose power consumption could be optimized by adapting the coverage and capacity of the individual base stations to the required load, and/or by using Multiple Input Multiple Output (MIMO) techniques in presence of more than one receiving and sending antennas. From the environmental impact perspective, we can reduce the overall carbon footprint by maximizing the use of renewable energy sources in both the transport and wireless access systems.

Clearly, a deep understanding of where and how the energy is used in communication infrastructures is absolutely needed to develop energy-aware control-plane frameworks capable of taking the right decisions in order to optimize energy consumption without impacting the overall network's performance. This implies the necessity of formulating a complete and realistic energy-model whose main purpose is providing a formal characterization of the energy consumption associated with the various network devices and link resources, its interactions with the current network load and the available power sources, together with the associated carbon footprint. The availability of this model has a paramount importance for the design and control of energy-aware routing protocols, or the evaluation of their power-saving and carbon-footprint reduction potential, by providing an estimate of the current and future power consumption of (some subset of) networks, and supporting optimal allocation policies for the available network links and renewable energy sources. Energy models have to be detailed enough to represent the complexity of the modeled systems, while being scalable and simple to implement, manage and modify according to new architectural and technological advances.

Accordingly, in order to formally characterize the energy consumption of all the available network elements within a modern Wireless Access-over-WDM infrastructure, we propose a comprehensive analytic model based on real energy consumption measurements and in line with the growth trends characterizing new energy-aware architectures that are capable of adapting dynamically their behavior depending on the current load, in order to minimize the energy consumption. Such a model, specifically designed to portrait as completely as possible only the network carrier perspective, does not consider the energy impacts of customer premise equipment or remote terminal nodes but restricts its interests and coverage to the wireless and wired access network (digital routers and radio access base stations) and to the optical (WDM-empowered) transport core, with the aim of ensuring flexibility and generality through a sufficiently high abstraction degree. This choice is motivated by the twofold consideration that, for the carriers' energy containment sakes, the consumption of the terminals is negligible with respect to the energy consumption of the access and transport networks, and on the other hand, from the terminal owners' perspective, energy-efficiency is already implicitly pursued since the terminals are already optimized in terms of energy consumption because they usually work by using batteries. In addition, the model has been specifically designed to take into consideration multiple energy sources, such as solar, wind, bio-energy and hydropower whose availability varies over time and weather conditions (e.g., night/day cycle, presence of wind, or waves, etc.) so that also carbon footprint optimization objectives can be simultaneously pursued. The energy usage characterization is based on a linear combinations of power consumption functions derived from experimental results and theoretical considerations keeping into account both electrical wired/wireless access and optical transport technologies, and differentiating the associated power consumption according to the various types of network devices and traffic flavors. Furthermore, the model does not support simplistic energy containment strategies based on putting into sleep mode entire devices, and the optimization relies only on the traffic-variable power consumption of the devices (assuming the knowledge of the amount of traffic exchanged by any source and destination nodes) and on the use of enhanced per-interface low power mode features.

The proposed formulation has the goal of minimizing both the overall GHG emissions and power consumption in future high speed mobile access and transport infrastructures, by allowing the setup of optimal network paths through a suitable energy-aware Routing and Wavelength Assignment (RWA) scheme, and hence can be considered as a reference for evaluating energy aware-routing strategies within the hybrid (multiple dynamic source) power system context of the modern Smart Grid infrastructure.

2. Related Work

Most of the available research and industrial literature proposing and evaluating energy-efficient or energy-aware solutions and schemes for modern network infrastructures are based on energy models built by considering the individual power consumption of a limited set of real world devices and only on a limited extent their power source. Nevertheless, it is often difficult to gather real energy consumption values, so it is not always feasible to create a complete mapping of real world devices, and it is practically impossible to measure energy consumption of future NEs architectures before designing and building them. However, in [6], [7], several routing/switching architectures have been analyzed and their energy consumptions under different traffic loads have been evaluated as a reference for modeling purposes. Also the work presented in [8] carefully analyzes the power consumption of core routers based on data sheets available from Juniper Networks Inc. and conclude that for higher throughputs the routers consume more power. Analogously, in [9] it is showed that circuit-based transport layer reduces energy consumption with respect to packet-switched layer, due to the lower processing required for managing connections and to the higher processing needed for analyzing each packets' headers.

An analytic energy model based on an ILP formulations for energy-efficient planning in WDM networks has been proposed in [10]. The authors identify three types of traffic: transmitting, receiving and switching traffic, though there is no difference between electronic and optical traffic. Another more sophisticated ILP formulation, also considering the energy source as a single static flag (clean, dirty) has been presented in [5], [11].

An energy consumption model for optical networks, differentiating its behavior depending on the network sub-domain (access, metro and core) has been proposed in [12]. Here, the power consumption in the core nodes is based on the energy efficiency of a typical core router, whereas the link power consumption is based on a channel efficiency value based on a typical WDM multiplexing/demultiplexing system together with its intermediate inline amplifiers. Such model has been generalized in [13] where it has been presented as a "transaction-based" model. The energy consumption in the wireless access system has been studied and modeled in [4], [14] by considering several kinds of access technologies, such as WiMax and UMTS. In [15] the author proposes a simple theoretical model in which the router energy consumption grows with a polynomial function of its capacity. This estimation results to be in line with the real energy consumption values reported some years after in [16], where a mixed energy model is presented. In this model the individual node energy consumption is modeled by averaging experimental data of a real network scenario, whilst the power consumption of links is analytically modeled by a static contribution due to optical transceivers, and by an additional term which takes into account possible (optical) regenerators.

To the best of our knowledge, our proposed model is the first experience in which a comprehensive wireless access-over-WDM scenario has been covered, by explicitly considering multiple green and dirty dynamically available energy sources. A further dimension in novelty comes from the assumption that node-wise sleep mode is not an acceptable choice [5], [10], allowing only per-interface *low power idle* (LPI) mode, so that the achievable energy savings come exclusively from the optimal routing of the connection requests.

3. Energy Models

An energy model for a network has the main goal of describing the energy consumption of all the available network elements (NE) and of estimating how such consumption varies under different conditions or traffic loads and for the diverse traffic types, including optical and electronic traffic, optical-electric-optical conversions, 3R (re-amplifying, reshaping, re-timing) regenerations, add/drop multiplexing, etc.. Basically, three different types of energy models have been reported in the literature [17]:

1. Analytic energy models.
2. Experimental energy models.
3. Theoretical energy models.

3.1. Analytic Energy Models

Analytic energy models [10] define the energy consumption of the available network elements by using a mathematical description of their operating environment. These models represent parametrically only the essential aspects of the available network elements and abstract all the other irrelevant details, in order to achieve a characterization of the energy consumption as realistic as possible. An analytic model has virtually the ability of describing the network energy consumption in any possible configuration. Furthermore, as irrelevant hardware, software and configuration details may be totally abstracted or only partially represented, the analytic models have the ability to scale well with the network size. Anyway, analytic models have some drawbacks as well. What has to be represented in the model and what should instead kept out is a design choice that has to be carefully planned, as an excessive degree of sophistication may introduce unnecessary complexity and unwanted behaviors. Furthermore, the complexity degree of the modeled devices should resemble as possible the real world devices, but it is not always possible to know the internal architecture details and the hardware technical specifications of some proprietary devices.

3.2. Experimental Energy Models

Experimental models [8], [9], [16] totally rely on known energy consumption values of real world devices. They are based on energy consumption values declared by the equipment manufacturers or on some experimentally measured values, to create a map of well-known off-the-shelf working device samples. Such map is then used for interpolating or extrapolating energy consumption data for network nodes of any size. Anyway, this model has several drawbacks. On the one hand, the declared energy consumptions may not closely resemble the real values especially when the device is working with a specific hardware and/or software configuration. On the other hand, although the experimentally measured energy consumption values may give an estimation of the variations in power demand under different traffic loads, they only refer to a punctual evaluation under specific assumptions. Furthermore, interpolation/extrapolation cannot be considered a reliable technique for the estimation of the energy consumption in real world devices, since such consumption may be subject to significant variations depending on specific technology, architecture, features and size (e.g., aggregated throughput, number of line cards, ports, wavelengths, etc.) properties. It should also be considered, that when aggregating over the entire network, the power consumption will also be larger on the network edge and smaller in the center. In addition, energy consumption also depends on the packets size and on the bit-rates of the links [17]. Transmitting packets with a bigger size requires less power than the one needed for smaller ones, due to the lower number of headers that have to be processed. In [9] it is showed that circuit-based transport layer reduces energy consumption with respect to packet-switched layer, due to the lower processing required for managing connections and to the higher processing needed for analyzing each packet headers. Nevertheless, it is often difficult to gather real energy consumption values, so it is not always feasible to create a complete mapping of real world devices, and it is practically impossible to measure energy consumption of future network elements architectures before designing and building them. So, an experimental model, though providing some real energy consumption values, is not flexible enough to cope with the requirements of a comprehensive energy model.

3.3. Theoretical Energy Models

In theoretical models such as [15], the energy consumption is expressed as a function of the load that tries to follow the trend of real devices power consumption. Being based on high level formulas and rules/laws, theoretical models are usually employed to describe in a simple though effective manner the relation between the energy consumption and the current traffic load. Such models have the benefit of being simple and clear, by providing significant easy-of-use advantages and no need for parameter tuning, but the predictions may substantially differ on the long run from the real energy consumption values. Besides, it is often difficult to foreseen the real energy consumptions for specific network devices and, since the available estimation rely only on empirical data, they should not be used as the bases for a rigorous scientific model. For this reason theoretical energy models do not provide detailed energy consumption for each subsystem or component, but they simply describe at an higher abstraction level the energy consumption at the expense of granularity and accuracy.

4. An Energy Model for Mobile Wireless Access-over-WDM Networks

The proposed energy model is based on a linear combinations of energy consumption functions derived from theoretical models [15], [18], [16] and experimental results [6], [8], [19], [7], [4] and specifically, it tries to combine all the notable features that a comprehensive hybrid-source energy-aware network model should have and put them together into a general Routing and Wavelength Assignment (RWA) framework. In doing this, all the energy-related information and concepts associated to devices and links have been abstracted and defined in a formal and concise way within the context of a specific energy-aware network optimization problem. This model, working on a network topology abstraction in which each node or link is characterized by a power consumption, varying under different loads, energy source and capacity, defines the basic energy requirements of each device by considering both electrical and optical technologies, and differentiates the consumption according to the various equipment flavors, traffic types and volumes.

4.1. The Reference Network Architecture

Most of the modern mobile ubiquitous data services, delivered over a variety of broadband wireless technologies, require advanced end-to-end bandwidth-guaranteed communication facilities between the mobile nodes and the service providers. These advanced services require a new generation network architecture that is powerful and yet flexible enough to enable fast changes. The typical architecture of general Mobile Data Networks may consist of public and private subnetworks implementing the transport infrastructure, or backbone, connecting several different radio access subsystems through specialized concentrator nodes or Access Routers (AR). The backbone may be built on high performance all-optical wavelength switches (optical cross connects, OXC) or hybrid optical/electric routers (digital cross connects, DXC) connected in a mesh of WDM-empowered fiber links. Mobile nodes are attached to radio access subsystems or Base Stations (BS) that can be viewed as legacy network nodes where mobile traffic originates and terminates. The radio access subsystem may typically consist of 802.11 access points in extended WLAN topologies, WiMax or UMTS/LTE Radio Access Network network elements that handle all radio-related functionality in their coverage environment. Whenever the coverage and capacity of a single radio access node does not suffice to fulfill the mobile connectivity requirements in a geographic area, we assume attachment of a sufficiently large number of access points to one or more ARs. The resulting mobile wireless access over WDM network must route dynamically and efficiently traffic over a technologically heterogeneous infrastructure according to the model proposed in [20]. In detail, mobile terminals generate bandwidth guaranteed end-to-end data flows over the radio links by attaching to base stations, that aggregate the associated technology-dependent traffic towards the Access Routers, to be transported across the backbone. The ARs behave as label switching edge nodes (LERs) within a GMPLS domain, integrating the mobile terminals in the label/wavelength switched network by managing the creation of *label switched paths* (LSPs) associated to mobile connections on Forwarding Equivalence Class or traffic flow basis. The internal backbone can be seen as one administrative domain entirely based on GMPLS technology, where the Switching Nodes provide support for traffic engineering, and label/wavelength switched paths management mechanisms.

4.2. Modeling the Network

In modeling the above reference architecture we consider mixed label/wavelength-routed networks in which the traffic unit is the end-to-end virtual circuit realized on both the optical transport core (*lightpath* [21]) and the electrical wired/wireless access domain (LSP). Such network can be modeled as a graph $G = (V, E)$ with $|V| = N$ nodes and $|E| = M$ edges (with an edge for each communication link, as shown in Figure 1).

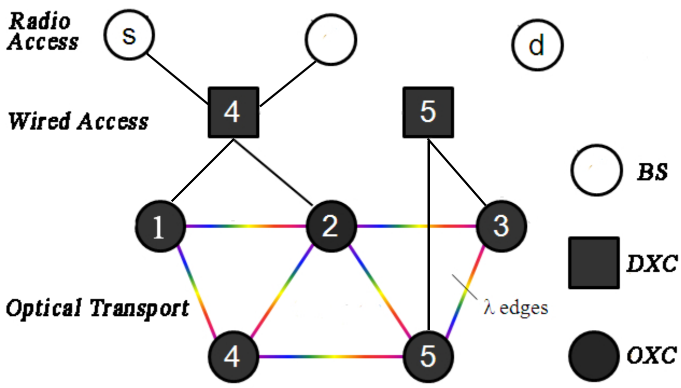

Figure 1: The network model.

Network nodes may represent wireless access base stations connected to active traffic exchange equipment such as electronic routers or optical switches connected by fiber links with up to λ wavelengths for each link.

Optical communication links can be characterized by multiple intermediate optical amplification (OA) or electrical regeneration (3R) stages. All the devices implementing intermediate stages on a communication link are assumed to be powered by the same energy source and to belong to the same family (i.e., the OAs are all of the same type/size

Table 1: Traffic supported by the available network elements.

Type of Device (NE)	Type of Traffic
Wireless Base Station	Electronic
Digital Router	Electronic
Optical Switch	Optical (with or without WC)
Optical Link	Optical (without WC)
Wireless Link	Electronic
Optical Amplifier	Optical (without WC)
3R Regenerator	Electronic

as well as all the 3R regenerators). The individual features of an optical link $e \in E$ are defined by the following parameters:

1. a_e: number of wavelengths available on link $e \in E$;
2. b_e: bandwidth capacity of link $e \in E$ in *Gbps;*
3. ℓ_e: length of link $e \in E$ in *km*;
4. Λ_{OA}: maximum length (in *km*) an optical signal can travel without need of optical amplification (80 *km*);
5. Λ_{3R}: maximum length (in *km*) an optical signal can travel without need of 3R regeneration (1000 *km*).

Wireless or direct electrical links are only characterized by a maximum bandwidth capacity b_e and maximum number of channels a_e but their individual impact (as objects within the energy model) from the energy-consumption perspective can be considered to be null, since they have no intermediate devices draining power from some energy source, and hence their energy consumption can be entirely associated to the interfaces (antenna or cable) of the terminating nodes.

Each of the above equipment has its own energy-related features with multiple different parameters influencing its consumption: device type, traffic, load, number of connected terminations, number of interfaces (ports), available energy saving modes, etc.. Table 1 reports the types of network element and the corresponding supported traffic types.

The aforementioned types of traffic account for different power consumption depending on the network element that is being traversed. In the proposed model three types of traffic are possible:

1. electronic traffic: opaque pass-through or wavelength/LSP routing/switching, add/drop multiplexing, traffic grooming, 3R regeneration, opaque wavelength conversion;
2. optical traffic without wavelength conversion: optical pass-through or optical by-pass totally transparent without wavelength conversion;
3. optical traffic with wavelength conversion: optical pass-through or optical by-pass totally transparent with wavelength conversion.

We assume that the traffic is unsplittable in the optical transport domain: i.e., a traffic demand is routed over a single lightpath. Conceptually, in the electronic domain a demand may be split into n flows, but in the optical domain these will appear as

Table 2: Operations supported in nodes and links with the associated parameters.

Operation	Nodes		Links	
	Electronic	Optical	Electronic	Optical
Routing	τ_n^{EL}			
WDM Switching	τ_n^{EL}			
Add & Drop	τ_n^{EL}			
3R regeneration	τ_n^{EL}		υ_e	
Wavelength Conversion	τ_n^{EL}	τ_n^{WC}		
Optical Amplification				ω_e
Transparent Pass-Trough		τ_n^{OP}		

n unsplittable optical flows. We also assume that all the nodes supporting the cross connect capability (i.e., except the access base stations) have the possibility to convert wavelengths, either in the electronic or in the optical domain, depending on their technology. In the electronic domain, the full range of operations is supported: wavelengths routing/switching, wavelengths add/drop, wavelength conversion, 3R regeneration. 3R regeneration can be realized on the communication link (every Λ_{3R} km) as well as in the nodes (a node $n \in V$ regenerates the signal whenever its OSNR falls below a certain threshold). In the optical domain the operations supported are optical amplification, only available on the transmission links, the transparent wavelength switching/pass-through and the wavelength conversion, that is available, either electronically or optically, only within the nodes. Table 2 resumes the considered operations in nodes and links.

4.3. Demand-related Parameters

The set of parameters characterizing the traffic demand in terms of end-to-end connection requests with their specific bandwidth requirements together with their associated lightpath/virtual circuit allocation on the network is reported in the following:

1. $B = \{1, 3, 12, 24, 48, 192, 768\}$ is the set of admissible bandwidths ranges for a request varying from 1 OC-unit (54 Mbps) to 768 OC-units (40 Gbps);
2. $T = \left\{t^b_{s,d} | s, d \in V \text{ and } b \in B\right\}$ is the set of demands to be routed in the network (the traffic matrix); $t^b_{s,d}$ is a demand from source node s to destination node d with required bandwidth b;
3. Π: set of paths (lightpaths or LSPs) routed in the network G; $\pi_t \in \Pi$ is the path satisfying the demand $t^b_{s,d} \in D$, i.e., a route (sequence of nodes and edges) connecting source node $s \in V$ to destination node $d \in V$ satisfying the bandwidth requirement of b Gbps. In order to simplify the notation, $n \in \pi_t$ will denote the set of nodes in the path π_t and $e \in \pi_t$ the set of edges in the path π_t. Clearly, given the demand $t^b_{s,d}$ and the lightpath π_i satisfying it, it holds that $\forall e \in \pi_t, b_e \geq b$;
4. x^π_n is a Boolean variable discriminating between electronic and optical traffic of the path $\pi \in \Pi$ at the node n:

$$x^\pi_n = \begin{cases} 1 & \text{if signal carrying traffic of lightpath } \pi \text{ is electrical in node } n \\ 0 & \textit{otherwise} \end{cases}$$

5. y_n^π is a Boolean variable discriminating whether the signal carrying traffic of lightpath π is optical without WC in node $n \in V$ or not;

$$y_n^\pi = \begin{cases} 1 & \text{if signal carrying traffic of lightpath } \pi \text{ is optical without WC in node } n \\ 0 & otherwise \end{cases}$$

6. z_n^π is a Boolean variable discriminating whether the signal carrying traffic of path π is optical with WC in node $n \in V$ or not:

$$z_n^\pi = \begin{cases} 1 & \text{if signal carrying traffic of lightpath } \pi \text{ is optical with WC in node } n \\ 0 & otherwise \end{cases}$$

7. $w_n^i$is a Boolean variable discriminating whether the interface (port) i of the node n is being used by any of the path $\pi \in \Pi$ traversing node $n \in V$ or not:

$$w_n^i = \begin{cases} 1 & \text{if the interface } i \text{ of the node } n \text{ is not being used by any of the lightpath traversing node } n \\ 0 & otherwise \end{cases}$$

We finally assume to have the complete knowledge of the amount of traffic exchanged by any source/destination node pair.

4.4. Power-related Parameters

The power consumption of the devices present on the network has been modeled by using two factors. When turned *on*, each NE consumes a constant amount of power (*fixed* power) depending on the node size and technology (measured in $J/s = W$) and independent on the traffic load. This amount of energy is always required just for the device to be powered on. The second factor (*proportional* power) consists of an amount of power proportional to the type and quantity of the traffic load (measured in *nJ/bit* or, equivalently, in *W/Gbps*). The overall power drained by the network is hence given by the sum of the fixed and proportional powers of all its NEs subject to the current traffic load and varying with the routing of the connection requests. This implies that, as the NEs are always turned on, the routing optimization process works "only" on the proportional power consumption factors.

The fixed and variable/proportional energy consumption factors may be defined as follows:

1. Θ_n: fixed power (W) of node n, depends on node size and equipment type;
2. τ_n^{EL}: proportional energy (*W/Gbps*) for transporting one bit of *electronic* traffic at node n (*wavelength routing/switching, add/drop multiplexing, traffic grooming, 3R regeneration, opaque wavelength conversion*);
3. τ_n^{OP}: proportional energy (*W/Gbps*) for transporting one bit of *optical* traffic at node n (*totally transparent traffic without wavelength conversion)*;
4. τ_n^{WC}: proportional energy (*W/Gbps*) for transporting and one bit of *optical* traffic at node n (*including optical wavelength conversion)*; in the Low Power Idle (LPI), an idle interface i of a node n consumes a small fraction $\rho_{idle}^{n,i} = 10\%$ of its power consumption in active mode $\tau_n^{t(i)}$, where $t(i)$ represents the type of interface (either electrical or optical);

5. Ω_e: fixed power (W) for optical amplifiers in link $e \in E$; we consider EDFA optical amplifiers that amplify all the C-band at once;
6. P_{OA}: proportional power (W) for optical amplifiers in link $e \in E$ needed every Λ_{OA} km of fiber. Since EDFAs amplify the entire C-band, the power ω_e per individual wavelength on edge $e \in E$ is given by $\omega_e = \frac{P_{OA}}{a_e}$, where a_e is the number of wavelengths available on link $e \in E$; all the OAs on the same link $e \in E$ share the same characteristics, energy sources and thus the same power consumption and GHG emissions;
7. Υ_e: fixed power (W) for 3R regenerators in link $e \in E$; 3Rs regenerate one wavelength at a time; all the 3R regenerator on the same link $e \in E$ have the same characteristics and share the same energy source, thus have the same power consumption and GHG emissions;
8. υ_e: proportional energy ($W/Gbps$) for 3R regenerators in link $e \in E$ needed every Λ_{3R} km of fiber. Since 3R regenerators work per-wavelength, it is needed one 3R regenerator for each wavelength to regenerate; all the 3Rs on the same link $e \in E$ have the same characteristics and share the same energy source, thus have the same power consumption and GHG emissions;
9. Υ_n: fixed power (W) for 3R regenerators in node $n \in V$; 3R regenerators for all the interfaces on the same node $n \in V$ have the same characteristics and share the same energy source, thus have the same power consumption and GHG emissions.

4.4.1. Switching/Routing Node Consumption

The power consumption of a generic switching node is dependent by its configuration and current usage. Several attributes characterize the configuration-dependent issues, such as the chassis type of the device, the installed line cards and interfaces. Some reference data about the power consumption of real electronic and optical switching nodes with and without WC are reported in [1], [6], [7], [22] where it can be observed that the base system of an idle device consumes approximately one half of the total power drained by the device, while the other half is consumed when the router is in its maximum configuration, i.e., maximum number of line cards/modules installed and operating at their full load. In our scheme, the usage-dependent part is conditioned from the properties of the traffic going through the device, which is the current rate on specific interfaces, together with their transmission and operating properties, thus the per-interface power consumption scales with the associated network load according to a statistical traffic model, that is, the absorption varies in a different way depending on the characterization and volume of traffic traversing the interface. In particular, interface may operate in one of a set of distinct states, corresponding to a family of distinct allowable link rates with their associated power demands. For abstraction and simplicity sake, our model does not take into account the specific power levels associated to the different available states for all the possible technologies, but binds these values to the notion of interface capacity. Furthermore, we assume that an interface may switch back and forth from low-power mode independently from the other interfaces on the same router or line card. The power draw p_n^i of an interface i of type $t(i)$ in the node n:

$$p_n^i = \vartheta_n^{t(i)} + \sum_{\pi_i \in \varpi(i)} \beta_{\pi_i} \cdot \tau_n^{t(i)} \tag{1}$$

can be expressed as the sum of a static part $\vartheta_n^{t(i)}$, and a dynamic one scaling with the set of paths $\varpi(i)$ traversing the interface i. The static part $\vartheta_n^{t(i)}$ is comprehensive of the fixed energy consumption of the interface itself together with the fixed power required by the associated 3R regeneration system (if any). Clearly the dynamic contribution, calculated by multiplying the current cumulative interface load with the proportional energy per bit, is null when the interface is in low power mode (and there is no traffic/paths). The dynamic component, is also dependent on the traffic type $t(i)$, accounting for the different requirements of the involved traffic. Both the components depend on a series of interface parameters such as architecture, technology, equipment, etc..

Clearly, the overall node power consumption will be given by the aggregate power absorption of all its active interfaces plus the reduced power consumption in idle interfaces, that are operating in low-power mode (LPI) when there is no data to transmit and quickly resumed when new input packets arrive.

$$P_n = \sum_{j \in L(n)} \sum_{i \in I(j)} \left(p_n^i + w_n^i \cdot \rho_{idle}^{n,i} \cdot \tau_n^{t(i)} \right) \quad (2)$$

where $L(n)$ is the set of line cards operating within the node n and $I(j)$ is the set of homogeneous interfaces belonging to a line card j. We have not considered line cards' specific absorption explicitly: their power draw is assumed to accrue that of the node chassis. The chassis adsorption is then uniformly split across all the interfaces.

Clearly, it is straightforward to observe that for the entire node n it holds that $\sum_{j \in L(n)} \sum_{i \in I(j)} \vartheta_n^{t(i)} = \Theta_n + \Upsilon_n$.

4.4.2. Base Station Node Consumption

As for the switching nodes also the power consumption of a base station is splittable in a fixed component, depending on its specific equipment and configuration in terms of radio interfaces, transceivers, coverage range, etc., and a variable/proportional power consumption that varies over time with the current load.

The base station has been modeled starting from its radio interfaces, each characterized by an antenna and a power amplifier, that is the component with the highest impact on the fixed power consumption. A multi-sector BS can have multiple radio interfaces. The effect of the other components can be easily modeled as it is a constant value depending on the type of interface. On the other hand, the power consumption of the power amplifier strongly depends on both the input power of the antenna and the efficiency of the power amplifier that in turn can be associated to the current coverage range. If, for the sake of abstraction, we assume that the coverage range of each antenna is kept fixed over time to a value depending on the interface type $t(i)$, we can model the fixed per-interface consumption $\vartheta_n^{t(i)}$ of the interface i on the node n as a constant component analogous to the one used in eq. (1). We also consider that the digital-related part of the per-interface power p_n^i scales according to the number of active wireless channels that in our model have a one-to-one correspondence with the number of paths $|\varpi(i)|$ traversing the wireless interface i. Consequently, also the dynamic part can be modeled as in eq. (1) as the product of the aggregate interface load with the proportional energy per bit. Inactive radio interfaces can be also put into low-power mode. As a direct consequence, the per-base station consumption is defined by the same eq. (2).

Some reference values about the power consumption of real base stations have been presented in [4], [14] for the UMTS ad WiMax technologies and in [23] for the LTE case.

4.4.3. Optical Communication Link Consumption

End-to-end transmission links are characterized by a power consumption depending not only on the specific demand associated with the hardware interfaces located in both the endpoints, but also on the impact introduced by the optical amplification and regeneration devices needed for the signal to reach the endpoints with an acceptable quality, and thus, on the length of the traversed fiber strands. The power consumption P_e of a link $e \in E$ can be modeled as:

$$P_e = \left\lfloor \frac{\ell_e}{\Lambda_{OA}} \right\rfloor \cdot (\Omega_e + \omega_e) + \left\lfloor \frac{\ell_e}{\Lambda_{3R}} \right\rfloor \cdot \left(\Upsilon_e + \sum_{\pi_i \in \varpi_e} \upsilon_e \cdot \beta_{\pi_i} \right) \tag{3}$$

where ϖ_e the set of paths traversing the link e.

4.5. Smart Grid-related Parameters

NEs may be powered either by green (renewable) or dirty (fossil-based) energy sources: that is, a hybrid system with multiple power-sources is assumed to be available in a subset (or all) the network sites. Clearly, green energy sources are always preferable with respect to the dirty ones as they limit (or avoid at all) GHG emissions, although, while fossil-based energy sources are always available, renewable sources are variable in nature and their availability may change in time (e.g., the sun varies with the day/night cycle, geographical position of the site, clouds; wind is not always blowing, etc.; even if batteries introduce a *safety margin* in the power provisioning, NEs cannot rely just on the renewable energy sources). Modern Smart-Grid infrastructures are able to dynamically switch the connections of renewable energy sources, according to their availability, and manage peak loads to allow for an improved efficiency of the generating assets. Ongoing research efforts aim at managing the future power grids as fully dynamic "cognitive energy systems", by applying modern cognitive control theories and techniques [24] to address the continuously evolving features of the modern grids. Therefore, we assume a smart grid-based [5] energy system in which NEs are provided with green energy sources alongside the legacy power system and, when necessary, they are able to switch to the fossil-based power supply without any energy interruption (e.g., at the UPS level). Such NEs are *energy-aware* since they adapt their behavior and performance depending not only on the current load but also on the source of energy that is supplying them. The type of (green and dirty) energy-sources that feeds each node is assigned to each NE at the network topology definition time; therefore, we consider a dynamic scenario in which the energy source that is *currently* powering the nodes may vary in time depending on the availability of the energy sources. We assume that each node is able to distinguish which power source is currently feeding it through the smart grid facilities and the energy-aware control plane intelligence. In addition, all the devices on a communication link are assumed to be powered by the same energy source and are all from the same family (i.e., the OAs are all of the same type/size as well as all the 3R regenerators).

The model has been explicitly designed to consider the presence of hybrid power systems potentially on each NE, so that nodes and devices on links may be individually

Table 3: Energy sources ordered by emissions.

ID	Energy Plant	Renewable	Emitted CO2/kWh	Mean value
0	Solar Wind Hydro-electrical	yes	0 g	0 g
1	Nuclear	no	6 – 34 g	20 g
2	Geothermal	yes	91 –122 g	107 g
3	Biomasses	yes	940 g	180 g
4	Natural Gas	no	370 g	370 g
5	Fuel	no	880 g	880 g
6	Coal	no	980 g	980 g

powered by several power sources, each with its own carbon footprint and σ_η is the carbon footprint (CO_2/W) of energy source currently powering network element η (e.g., a node, an OA, a 3R regenerator, etc.). The mean values for σ_η, together with the set of the possible energy sources (energy plants) are reported in last column of Table 3, where only the emissions occurring during the use phase are considered, without accounting for other adverse environmental effects associated to fuel preparation and waste dismissal, if any. However, it should be kept in mind that nuclear energy, although does not emit considerable quantities of CO_2 has other severe impacts on the environment and is not renewable since its fuel (mainly uranium and plutonium) is available only in limited quantity. Also geothermal energy can be considered as a limited-life renewable source because the continuous exploitation of a geothermal source may induce a progressive reduction of its efficiency. A final remarks, is needed for biomass-generated energy, whose emissions are partially compensated by the CO_2 absorption during biomass production (i.e., the growing plants), usually approximated with a value of 0.18 kg/kWh [10], [8], [9], [16].

4.6. Estimating Power Consumption and Carbon Footprint

Starting from these assumptions, we can estimate the power consumption and GHG emissions on a per-path basis, so that we can leverage on these information to build specific objective functions that can be used to drive energy-aware RWA schemes.

In detail, an energy-aware RWA scheme operating on Wireless Access-over-WDM networks with hybrid power sources has to evaluate the power consumption P_{π_t} and/or the carbon footprint C_{π_t} of a path π_t to make its decision on the path to be selected for routing each connection demand t. Since the optimal selection of paths satisfying multiple independent requirements, objectives and constraints is a computationally intractable problem, clearly not affordable in a dynamic on-line RWA environments, the above function can be use to implement proper heuristics in order to effectively select feasible paths, leading to sub-optimal solutions, and according to specific policies, in a bounded time. In particular, the knowledge about the energy source and its dynamic behavior, can be included in the control plane algorithms by properly tuning the energy source related parameters σ_η to properly condition energy-aware routing, signaling and resource allocation, in order to implement specific energy-related policies such as *follow the sun, follow the tide, etc.*. This also allows the implementation of adaptive network re-optimization strategies that reconfigure the network dynamically, by considering the new distribution of available clean energy and re-optimizing its carbon footprint.

Given the demand $t^b_{s,d} \in D$, the power consumption of the lightpath $\pi_t \in \Pi$ satisfying the demand $t^b_{s,d}$ is given by the following formula:

$$P_{\pi_t} = \underbrace{\beta_{\pi_t} \sum_{n \in \pi_t} \left[\underbrace{\tau_n^{EL} \cdot x_n^{\pi}}_{\text{electronic}} + \underbrace{\tau_n^{OP} \cdot y_n^{\pi}}_{\text{optical w/o WC}} + \underbrace{\tau_n^{WC} \cdot z_n^{\pi}}_{\text{optical w/ WC}} \right]}_{\text{node}} + \underbrace{\sum_{e \in \pi_t} \left[\underbrace{\left\lfloor \frac{\ell_e}{\Lambda_{OA}} \right\rfloor \cdot \omega_e}_{\text{optical amplifiers}} + \underbrace{\left\lfloor \frac{\ell_e}{\Lambda_{3R}} \right\rfloor \cdot \upsilon_e \cdot \beta_{\pi_t}}_{\text{3R regeneration}} \right]}_{link}; \tag{4}$$

from eq. (4), the carbon footprint C_{π_t} of path π_t is given by:

$$C_{\pi_t} = \underbrace{\beta_{\pi_t} \sum_{n \in \pi_t} \sigma_n \cdot \left[\underbrace{\tau_n^{EL} \cdot x_n^{\pi}}_{\text{electronic}} + \underbrace{\tau_n^{OP} \cdot y_n^{\pi}}_{\text{optical w/o WC}} + \underbrace{\tau_n^{WC} \cdot z_n^{\pi}}_{\text{optical w/ WC}} \right]}_{\text{node}} + \underbrace{\sum_{e \in \pi_t} \sigma_e \cdot \left[\underbrace{\left\lfloor \frac{\ell_e}{\Lambda_{OA}} \right\rfloor \cdot \omega_e}_{\text{optical amplifiers}} + \underbrace{\left\lfloor \frac{\ell_e}{\Lambda_{3R}} \right\rfloor \cdot \upsilon_e \cdot \beta_{\pi_t}}_{\text{3R regeneration}} \right]}_{link}. \tag{5}$$

The fixed power consumption of the whole network G will be given by:

$$P_{G(V,E)}^{fixed} = \underbrace{\sum_{n \in V} \left(\underbrace{\Theta_n}_{\text{basesystem}} + \underbrace{\Upsilon_n}_{\text{3R regenerator}} + \underbrace{\sum_{i \in n} w_n^i \cdot \rho_{idle}^{n,i} \cdot \tau_n^{t(i)}}_{\text{idle interfaces}} \right)}_{\text{node}} + \underbrace{\sum_{e \in E} \left[\underbrace{\left\lfloor \frac{\ell_e}{\Lambda_{OA}} \right\rfloor \cdot \Omega_e}_{\text{optical amplifiers}} + \underbrace{\left\lfloor \frac{\ell_e}{\Lambda_{3R}} \right\rfloor \cdot \Upsilon_e}_{\text{3R regenerators}} \right]}_{link}. \tag{6}$$

We can also determine the per-network (total) power consumption as the sum of the fixed power consumption of all the NEs and the variable power consumption induced by all the paths/virtual circuits currently established on the network.

Given eq. (4) and (6), the total (fixed + variable) power consumption of the network $G(V,E)$ evaluated in the chosen energy model will be given by:

$$P_{G(V,E)}^{Tot} = P_{G(V,E)}^{fixed} + \sum_{\pi_t \in \Pi} P_{\pi_t} \tag{7}$$

Analogously, from eq. (6) and (7) we can also derive the total carbon footprint $C_{G(V,E)}^{Tot}$ of the network $G(V,E)$, given by:

$$C^{Tot}_{G(V,E)} = \underbrace{\underbrace{\sum_{n \in V} \sigma_n \cdot \left(\underbrace{\Theta_n}_{\text{basesystem}} + \underbrace{\Upsilon_n}_{\text{3R regenerator}} + \underbrace{\sum_{i \in n} w^i_n \cdot \rho^{n,i}_{idle} \cdot \tau^{EL}_n}_{\text{idle interfaces}} \right)}_{\text{node}} + \underbrace{\sum_{e \in E} \sigma_e \cdot \left[\underbrace{\left\lfloor \frac{\ell_e}{\Lambda_{OA}} \right\rfloor \cdot \Omega_e}_{\text{optical amplifiers}} + \underbrace{\left\lfloor \frac{\ell_e}{\Lambda_{3R}} \right\rfloor \cdot \Upsilon_e}_{\text{3R regeneration}} \right]}_{link}}_{\text{carbon footprint of } P^{fixed}_{G(V,E)}} +$$

$$+ \sum_{\pi_t \in \Pi} \underbrace{\left\{ \underbrace{\beta_{\pi_t} \sum_{n \in \pi_t} \sigma_n \cdot \left[\underbrace{\tau^{EL}_n \cdot x^\pi_n}_{\text{electronic}} + \underbrace{\tau^{OP}_n \cdot y^\pi_n}_{\text{optical w/o WC}} + \underbrace{\tau^{WC}_n \cdot z^\pi_n}_{\text{optical w/ WC}} \right]}_{\text{node}} + \underbrace{\sum_{e \in \pi_t} \sigma_e \cdot \left[\underbrace{\left\lfloor \frac{\ell_e}{\Lambda_{OA}} \right\rfloor \cdot \omega_e}_{\text{optical amplifiers}} + \underbrace{\left\lfloor \frac{\ell_e}{\Lambda_{3R}} \right\rfloor \cdot \upsilon_e \cdot \beta_{\pi_t}}_{\text{3R regeneration}} \right]}_{link} \right\}}_{\text{carbon footprint of } P_{\pi_t}}. \tag{8}$$

Note that the *fixed* power consumptions term in eq. (6), (7) and (8) are not involved in the optimization process (as per-node sleep mode is assumed not to be possible, fixed power consumptions are always present and the optimization relies only on the variable energy consumptions). It should also be considered that some of the model parameters (e.g., Θ_n, Ψ_n, etc.) are fixed at network definition time and may vary only rarely (e.g., upon node or link fail, updating processes, etc.); others, instead, are highly variable with time and they need to be updated during the network operation time. Hence, when implementing the proposed model into a real RWA scheme, several enhanced control plane routing/announcing and signaling facilities are needed for the timely propagation of all the dynamic energy-related information needed.

Nevertheless, the final goal of an energy-aware RWA scheme empowered by smart-grid facilities providing multiple dynamic energy sources, is the minimization of the network power consumption due to the network elements powered by dirty energy sources (as we want to minimize GHG emissions, by reducing the carbon footprint) and – among the solutions at minimum power consumption – the minimization of the total power consumption of the network. This can be achieved according to a multi-objective decision schema taking into consideration the minimization of the total carbon footprint $C^{Tot}_{G(V,E)}$, and simultaneously minimizing the total network power consumption $P^{Tot}_{G(V,E)}$.

The resulting objective function will be:

$$\min_X \left[C^{Tot}_{G(V,E)}(x), P^{Tot}_{G(V,E)}(x) \right]^T \tag{9}$$

where X is the aggregate vector of decision variables characterizing the whole model.

In this case, since we have more that one objective function, the notion of "optimum" changes, because in multi-objective optimization, the main goal becomes finding good compromise (or "trade-off") solutions rather than a single solution as in global optimization. Formally, the solution to the above problem is a possibly infinite set of *Pareto points*, thus, when aggregating both the objectives into a single objective function we are interested in an heuristic weighted combination of the above functions whose solution points are on or near to some of these Pareto points.

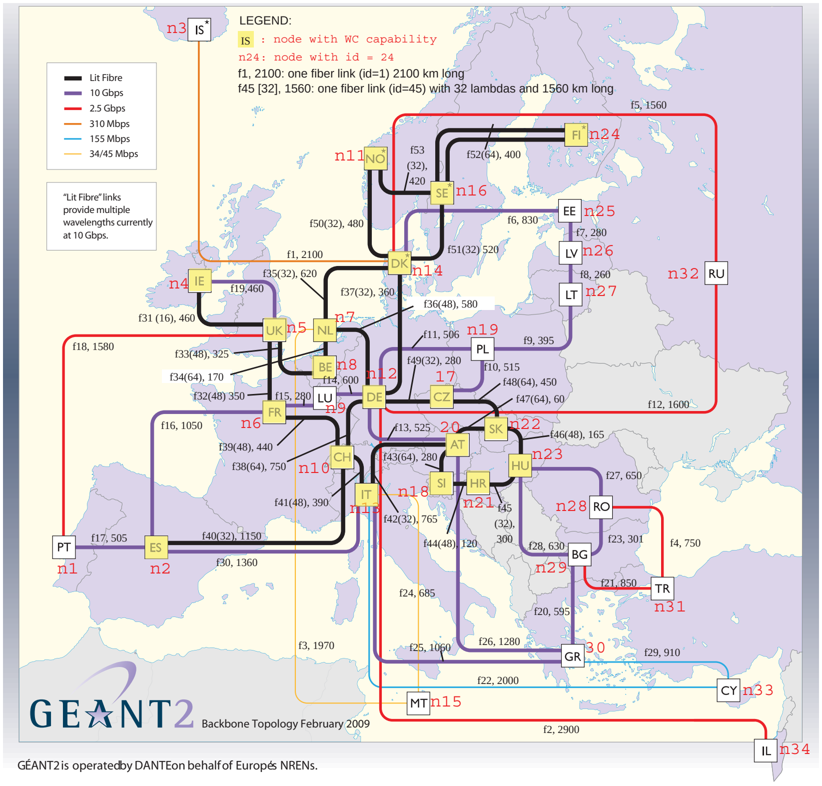

Figure 2: The Geant2 network topology used for simulation. Each node is made up of an electronic router plus an optical switch connected with one fiber link 1 km long, with 32 lambdas, each lambda at 48 OC-unit.

5. Experimental Evaluation

In order to experimentally validate our model, we first analyzed the node power consumption of eq. (2) when no traffic is being routed at all. In such a network configuration, the fixed power consumption of nodes is given by the base system plus the (reduced) power consumption of all its idle interfaces that are operating in low-power mode (LPI).

In the considered network topology (modeled starting from the Geant2 network reference reported in Figure 2), nodes configuration differ for the chassis type and the class and number of installed line cards and interfaces. As a result, the fixed per-node power consumption, evaluated in our energy model and shown in Figure 3, differs for each node, according to its configuration. The last reported values in the figure refer to small peripheral nodes (25-34) whose power consumption minimally affects the overall power budget of the network.

Nodes located in the center of the network tend to be bigger, in terms of aggregated bandwidth capacity, line cards and interfaces, and will have higher energy consumption with respect to peripheral nodes which are usually smaller.

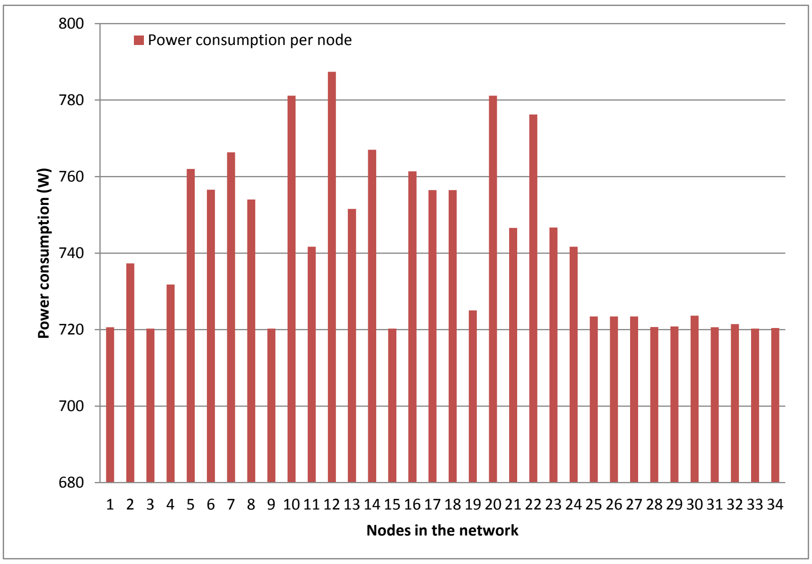

Figure 3: Fixed per-node power consumption.

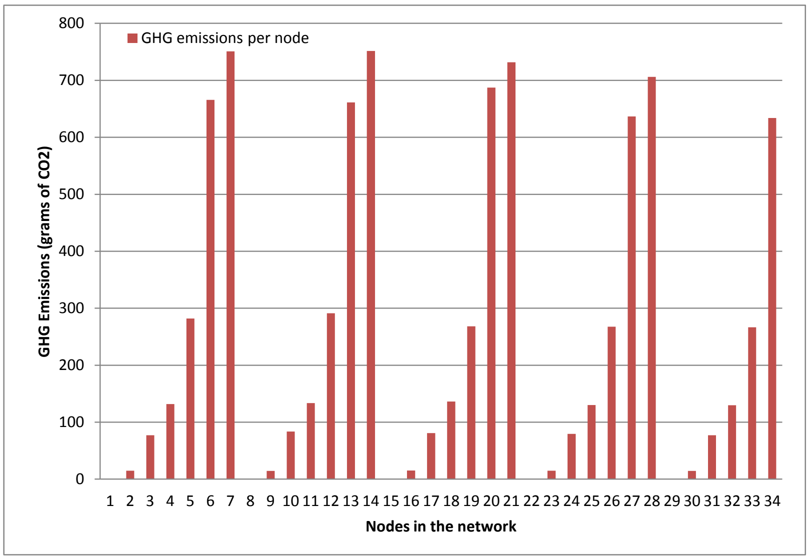

Figure 4: Fixed per-node GHG emissions.

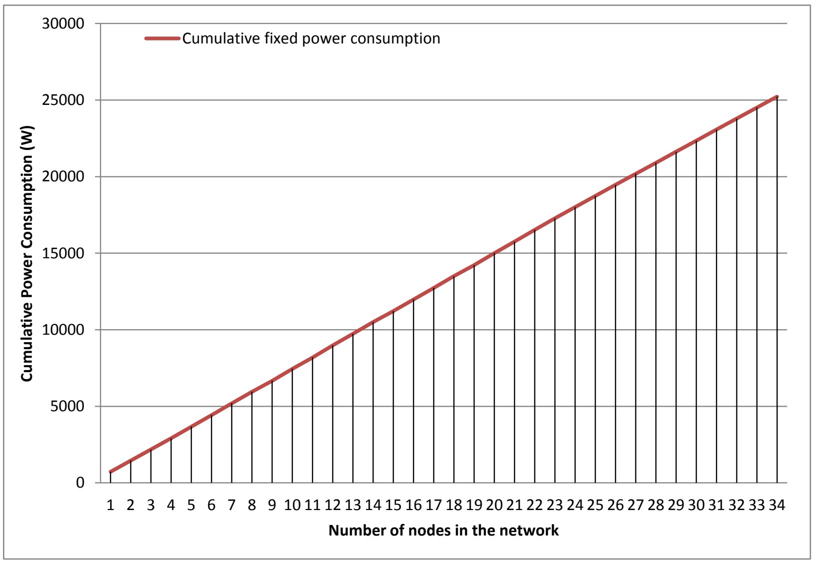

Figure 5: Cumulative fixed power consumption of network nodes.

In the initial configuration, the energy-source is assigned to the nodes in a round-robin fashion, from the least to the most emitting ones (see Table 3). The round-robin assignment has been chosen in order to uniformly distribute the different energy sources to the network nodes (actually a totally random assignment would be as effective as the round robin). In fact, it is worth to note that the initial assignment of the energy sources has little or no impact on the variable (thus, optimizable) power consumption *on the long run*. The daily variation in the green power sources availability would eventually cancel the initial assignment in a 24h period of time.

As a consequence, the most energy consumer nodes are not always the most emitting ones, since they may be powered by a green energy source, and relative small nodes powered by dirty energy sources may become the most emitting ones. The per-node GHG emissions evaluated in our energy model is reported in Figure 4. We can observe that the per-node GHG emissions follow a much more regular trend, in spite of the uneven nodes characteristics and power consumptions; the resulting GHG emissions are much more a function of the energy source type than of the node size or class of its interfaces.

However, even if the nodes of the considered network differ in class, type and number of line cards and interfaces, and thus in their individual power consumptions, it can be observed from Figure 5 that the overall fixed power consumption of the network nodes scales linearly with the number of devices.

However, the linear growth in the cumulative power consumption of the network reveals an irregular growth in the GHG emissions (Figure 6), since each node will contribute differently to the emissions according to the energy source that is currently powering it.

Such results, somehow straightforward, are used to experimentally validate our model against the fixed power consumption of the network nodes, which are the most power

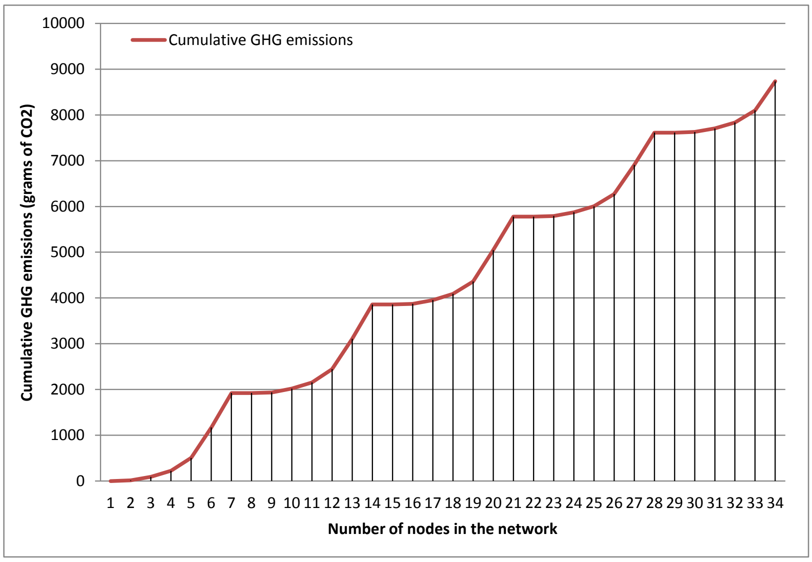

Figure 6: Cumulative fixed GHG emissions of network nodes.

consuming and GHG emitting devices in a network.

The next block of results focus on the variable power consumption and GHG emissions of the network, involving also network links, with associated optical amplification and 3R regeneration of the signals carrying the traffic load.

Results are presented distinguishing two *pure* optimization objectives, namely *MinPower* and *MinGHG*, which optimize the overall power consumption and GHG emissions respectively. The optimization of MinPower and MinGHG relies in the minimization of the traffic-variable power consumption and GHG emissions, by choosing the paths that crosses the less power consuming or less emitting network elements. Besides, the shortest path first (SPF) algorithm is also presented for comparison. The SPF algorithm always routes the connections on the shortest paths (minimum number of hops) and is totally energy and GHG-unaware.

The power consumption of the three algorithms has been plotted in Figure 7. It can be observed that MinPower minimizes the power consumption of the network, showing a lower than linear growth in the number of connection requests. On the other hand, MinGHG presents a sharper power consumption with respect to MinPower. Such a behavior is due to the different optimization objectives of the two functions. MinGHG is, in fact, completely unaware of the power consumption of the traversed NEs, basing its choices only on the energy sources powering them. The SPF algorithm consumes slightly more power than MinPower but less than MinGHG, since SPF always chooses the shortest paths which on average result less power consuming than the ones chosen by MinGHG.

In spite of consuming more energy than both MinPower and SPF, MinGHG strategy results in a drastic decrement of the emitted GHGs, as can be seen in Figure 8. This graphic shows that the GHG emissions of the considered network can be lowered at almost

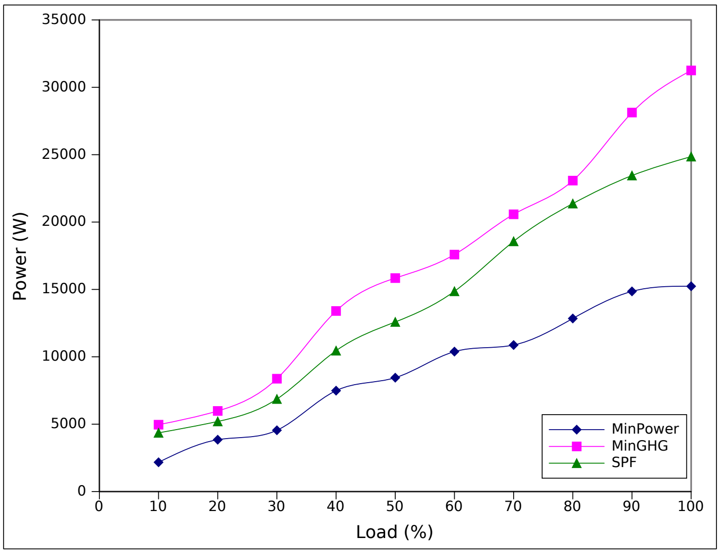

Figure 7: Network-wide variable power consumption *vs* traffic load.

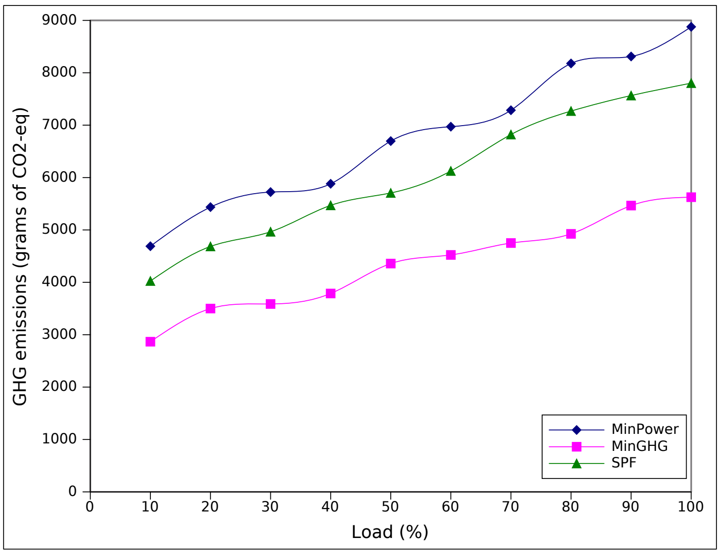

Figure 8: Network-wide GHG emissions due to variable power consumption *vs* traffic load.

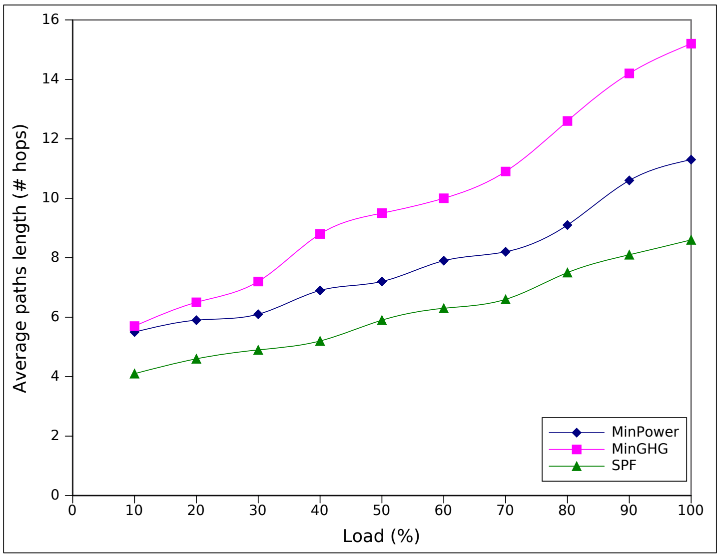

Figure 9: Average paths length *vs* traffic load.

one half of those of an GHG-unaware scheme, as MinPower. As expected, MinPower will emit more GHGs than both MinGHG and SPF, since its choices are based exclusively on the power consumption of the traversed network elements. It is interesting to note that the SPF algorithm, by limiting the length of the path, indirectly contains the power consumption and the GHG emissions. However, its too simplistic behavior results in high congestion on the shortest paths and, therefore, on high blocking probability.

It is worth to note the difference between a pure energy-aware (MinPower) and a pure GHG-aware (MinGHG) routing scheme. The energy consumption is, in fact, *strictly* additive in nature, in the sense that each traversed NE adds some (> 0) energy consumption to the overall energy budget of the network. Green house gases emissions, instead, are not *strictly* additive, in the sense that NEs powered by totally green energy sources (such as sun, wind and tide) can be traversed without adding emissions to the overall network carbon footprint and, indeed, will be preferred when evaluating the convenience of paths. This results, on average, in longer paths chosen by the MinGHG strategy with respect to MinPower. Such a behavior can be observed in Figure 9, where the average paths length obtained by the two optimization strategies is plotted against the traffic load. It can be noted that, at low loads, both strategies achieve to connect the requested source-destination pairs with almost the same paths length (always higher than the average paths length obtained by SPF), since there are enough network resources to choose among. However, as the traffic load increases, a prominent increment in the length of the MinGHG paths is reported, proving that, for the same traffic load requests, MinGHG prefers longer but *greener* paths with respect to MinPower which, on the other side, prefers shorter but *more emitting* paths, due to the strictly additive nature of the power consumption.

The intuition that the longer paths chosen by MinGHG are greener than the shorter ones chosen by the MinPower strategy, is further confirmed by the last graphic shown in

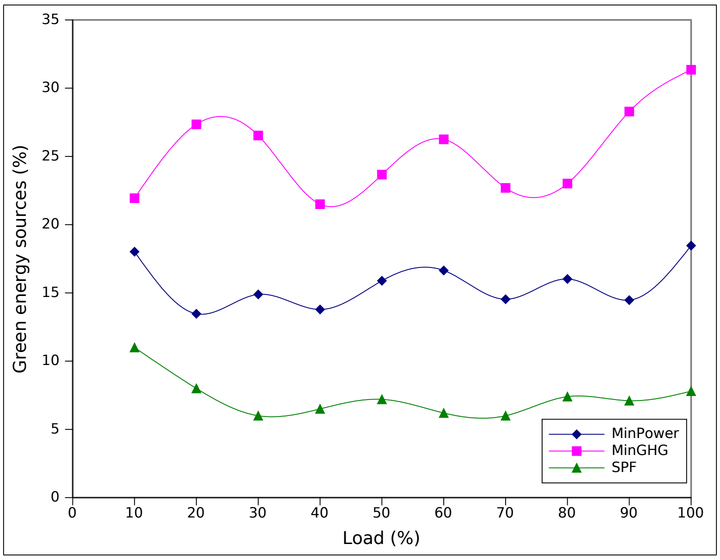

Figure 10: Green energy sources share *vs* traffic load.

figure 10, in which the percentage of the green energy sources is reported. Here, for green energy sources, we mean solar, wind and hydro-electrical (energy sources with ID=0 in Table 3). Clearly, MinGHG achieves an higher percentage of green energy sources with respect to MinPower, approximately 25% of share against 16%. The SPF is the algorithm which worst performs, even if it presents a more regular trend, not being affected in its choices by green criteria. In all graphics, an oscillation can be observed, more prominent in MinGHG. This is due to the availability of such green energy sources, which follows a more regular trend due to the cyclic nature of the involved phenomena.

6. Conclusions

In order to lower the energy consumption and the concomitant GHG emissions of modern broadband communication infrastructures, it is necessary to assess the power consumption of current and future energy-efficient network architectures through extensive and complete energy models that characterize the behaviors of the involved equipment. For this purpose, we presented a comprehensive energy model which accounts for the foreseen energy-aware architectures and the grow rate predictions, including different types of traffic of a Wireless Access-over-WDM network. The model, based on real energy consumption considerations, tries to collect the main benefits of the already available models while introducing modern concepts and flexibility features such as the support for per-device dynamically configurable hybrid power system, where statistically variable green energy sources may be considered within a totally dynamic scenario in which the availability of the different types of renewable energy sources can be associated with the variations of the day time and traffic load (e.g., night/day cycle). In addition, it allows modeling for a large extent on network devices and auxiliary equipment and supports low power idle mode an any optical or electric (wired/wireless) communication interface. As a final result, the presented model also maintained low complexity and, thus, high scalability. We believe that such an energy model will help the development of new energy-aware network architectures for achieving sustainable society growth and prosperity.

7. Acknowledgments

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References

[1] B. project, WP 21 TP green optical networks, D21.2b report on Y1 and updated plan for activities (2009).
URL `http://www.ict-bone.eu/portal/landing_pages/bone_deliverables/bone_216863_-_d21-2b_-_report_y1.pdf`

[2] M. Pickavet, W. Vereecken, S. Demeyer, P. Audenaert, B. Vermeulen, C. Develder, D. Colle, B. Dhoedt, P. Demeester, Worldwide energy needs for ict: The rise of power-aware networking, in: Advanced Networks and Telecommunication Systems, 2008. ANTS'08. 2nd International Symposium on, IEEE, 2008, pp. 1–3.

[3] M. Etoh, T. Ohya, Y. Nakayama, Energy consumption issues on mobile network systems, in: Applications and the Internet, 2008. SAINT 2008. International Symposium on, IEEE, 2008, pp. 365–368.

[4] M. Deruyck, W. Vereecken, E. Tanghe, W. Joseph, M. Pickavet, L. Martens, P. Demeester, Power consumption in wireless access network, in: Wireless Conference (EW), 2010 European, IEEE, 2010, pp. 924–931.

[5] S. Ricciardi, D. Careglio, G. Santos-Boada, J. Solé-Pareta, U. Fiore, F. Palmieri, Towards an energy-aware internet: modeling a cross-layer optimization approach, Telecommunication Systems (2011) 1–22.

[6] J. Chabarek, J. Sommers, P. Barford, C. Estan, D. Tsiang, S. Wright, Power awareness in network design and routing, in: INFOCOM 2008. The 27th Conference on Computer Communications. IEEE, IEEE, 2008, pp. 457–465.

[7] W. Van Heddeghem, F. Idzikowski, W. Vereecken, D. Colle, M. Pickavet, P. Demeester, Power consumption modeling in optical multilayer networks, Photonic Network Communications (2012) 1–17.

[8] W. Vereecken, W. Van Heddeghem, D. Colle, M. Pickavet, P. Demeester, Overall ict footprint and green communication technologies, in: Communications, Control and Signal Processing (ISCCSP), 2010 4th International Symposium on, IEEE, 2010, pp. 1–6.

[9] M. Feng, K. Hinton, R. Ayre, R. Tucker, Reducing ngn energy consumption with ip/sdh/wdm, in: Proceedings of the 1st international conference on energy-efficient computing and networking, ACM, 2010, pp. 187–190.

[10] A. Muhammad, P. Monti, I. Cerutti, L. Wosinska, P. Castoldi, A. Tzanakaki, Energy-efficient wdm network planning with dedicated protection resources in sleep mode, in: Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE, IEEE, 2010, pp. 1–5.

[11] S. Ricciardi, D. Careglio, F. Palmieri, U. Fiore, G. Santos-Boada, J. Solé-Pareta, Energy-aware rwa for wdm networks with dual power sources, in: Communications (ICC), 2011 IEEE International Conference on, IEEE, 2011, pp. 1–6.

[12] J. Baliga, R. Ayre, K. Hinton, W. Sorin, R. Tucker, Energy consumption in optical ip networks, Journal of Lightwave Technology 27 (13) (2009) 2391–2403.

[13] D. Kilper, G. Atkinson, S. Korotky, S. Goyal, P. Vetter, D. Suvakovic, O. Blume, Power trends in communication networks, Selected Topics in Quantum Electronics, IEEE Journal of 17 (2) (2011) 275–284.

[14] J. Baliga, R. Ayre, K. Hinton, R. Tucker, Energy consumption in wired and wireless access networks, Communications Magazine, IEEE 49 (6) (2011) 70–77.

[15] R. Tucker, Modelling energy consumption in ip networks, in: Cisco Green Research Symposium, 2008.

[16] W. Van Heddeghem, M. De Groote, W. Vereecken, D. Colle, M. Pickavet, P. Demeester, Energy-efficiency in telecommunications networks: link-by-link versus end-to-end grooming, in: Optical Network Design and Modeling (ONDM), 2010 14th Conference on, IEEE, 2010, pp. 1–6.

[17] S. Ricciardi, D. Careglio, F. Palmieri, U. Fiore, G. Santos-Boada, J. Solé-Pareta, Energy-oriented models for wdm networks, Broadband Communications, Networks, and Systems (2012) 534–548.

[18] L. Chiaraviglio, M. Mellia, F. Neri, Energy-aware backbone networks: a case study, in: Communications Workshops, 2009. ICC Workshops 2009. IEEE International Conference on, IEEE, 2009, pp. 1–5.

[19] K. Christensen, B. Nordman, Reducing the energy consumption of networked devices, IEEE 802.3 tutorial.

[20] F. Palmieri, An mpls-based architecture for scalable qos and traffic engineering in converged multiservice mobile ip networks, Computer Networks 47 (2) (2005) 257–269.

[21] Z. Bogdanowicz, S. Datta, Analysis of backup route reoptimization algorithms for optical shared mesh networks, Mathematical and Computer Modelling 40 (9-10) (2004) 1047–1055. doi:10.1016/j.mcm.2004.02.030.

[22] S. Aleksic, Analysis of power consumption in future high-capacity network nodes, IEEE/OSA Journal of Optical Communications and Networking 1 (3) (2009) 245–258. doi:10.1364/JOCN.1.000245.

[23] C. Desset, B. Debaillie, V. Giannini, A. Fehske, G. Auer, H. Holtkamp, W. Wajda, D. Sabella, F. Richter, M. Gonzalez, et al., Flexible power modeling of lte base stations, in: Wireless Communications and Networking Conference (WCNC), 2012 IEEE, IEEE, 2012, pp. 2858–2862.

[24] L. Ogiela, M. R. Ogiela, Advances in Cognitive Information Systems, Cognitive Systems Monographs vol. 17, Springer-Verlag, Berlin-Heidelberg, 2012.

8. Authors Biographies

Sergio Ricciardi is a research associate in the Advanced Broadband Communications Center (CCABA) at the Department of Computer Architecture of the Technical University of Catalonia - BarcelonaTECH (UPC). He holds a PhD in Computer Architecture from the UPC and two Masters of Science in Computer Science from the University of Naples Federico II and the UPC. He worked within the Italian National Institute for Nuclear Physics (INFN) in the CERN LHC Atlas experiment and he is currently involved in several national and international projects. His research interests are mainly focused on energy-aware RWA algorithms and protocols for telecommunication networks and energy-oriented optimizations for grid/cloud computing.

Francesco Palmieri is an assistant professor at the Engineering Faculty of the Second University of Napoli, Italy. His major research interests concern high performance and evolutionary networking protocols and architectures, routing algorithms and network security. Since 1989, he has worked for several international companies on networking-related projects and, starting from 1997, and until 2010 he has been the Director of the telecommunication and networking division of the Federico II University, in Napoli, Italy. He has been closely involved with the development of the Internet in Italy as a senior member of the Technical-Scientific Advisory Committee and of the CSIRT of the Italian NREN GARR. He has published a significant number of papers in leading technical journals and conferences and given many invited talks and keynote speeches.

Ugo Fiore leads the Network Operations Center at the Federico II University, in Naples. He began his career with Italian National Council for Research and has also more than 10 years of experience in the industry, developing software support systems for telco operators. His research interests focus on optimization techniques and algorithms aiming at improving the performance of high-speed core networks. He is also actively pursuing two other research directions: the application of nonlinear techniques to the analysis and classification of traffic; security-related algorithms and protocols.

Aniello Castiglione joined the Dipartimento di Informatica ed Applicazioni "R. M. Capocelli" of University of Salerno in February 2006. He received a degree in Computer Science and his Ph.D. in Computer Science from the same university. He is a reviewer for several international journals (Elsevier, Hindawi, IEEE, Springer, Inderscience) and he has been a member of international conference committees. He is a Member of various associations, including: IEEE (Institute of Electrical and Electronics Engineers), of ACM (Association for Computing Machinery), of IEEE Computer Society, of IEEE Communications Society, of GRIN (Gruppo di Informatica) and of IISFA (International Information System Forensics Association, Italian Chapter). He is a Fellow of FSF (Free Software Foundation) as well as FSFE (Free Software Foundation Europe). For many years, he has been involved in forensic investigations, collaborating with several Law Enforcement agencies as a consultant. His research interests include Data Security, Communication Networks, Digital Forensics, Computer Forensics, Security and Privacy, Security Standards and Cryptography.

Germán Santos-Boada obtained his M.Sc. degree in Telecom Engineering in 1978, and his Ph.D. in 1993, both from the Technical University of Catalonia (UPC). He worked for Telefónica as manager of engineering from 1984 up to 2007 and simultaneously he joined the Computer Architecture Department of UPC as a partial time Assistant Professor. Currently he is full time Assistant Professor with this department. Dr. Santos current research interests are Quality of Service provisioning in next generation optical access networks and optical energy-aware network modeling. He is currently involved in the COST 804 action.