Energy-Oriented Models for WDM Networks

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Abstract. A realistic energy-oriented model is necessary to formally characterize the energy consumption and the consequent carbon footprint of actual and future high-capacity WDM networks. The energy model describes the energy consumption of the various network elements (NE) and predicts their energy consumption behavior under different traffic loads and for the diverse traffic types, including all optical and electronic traffic, O/E/O conversions, 3R regenerations, add/drop multiplexing, etc. Besides, it has to be scalable and simple to implement, manage and modify according to the new architecture and technologies advancements. In this paper, we discuss the most relevant energy models present in the literature highlighting possible advantages, drawbacks and utilization scenarios in order to provide the research community with an overview over the different energy characterization frameworks that are currently being employed in WDM networks. We also present a comprehensive energy model which accounts for the foreseen energy-aware architectures and the growth rate predictions which tries to collect the main benefits of the previous models while maintaining low complexity and, thus, high scalability.

Keywords: Energy-oriented models, evolutionary energy-aware WDM networks.

1 Introduction

It is now held as a scientific fact that humans contribute to the global warming of planet Earth through the release of carbon dioxide (CO_2), a Green House Gas (GHG), in the atmosphere. Recently, the carbon footprint of ICT was found to be comparable to that of aviation [1]. It is estimated that 2-3% of the CO_2 produced by human activity comes from ICT [2][3] and a number of studies estimate an energy consumption related to ICT varying from 2% to 10% of the worldwide power consumption [4]. It is worth to mention for example that Telecom Italia and France Telecom are now the second largest consumer of electricity in their country [5][6] and British Telecom is the largest single power consumer in the UK [7].

The reduction and optimization of energy consumption are among the main goals of the European Union (EU). The EU in fact is encouraging the ICT sector to reduce

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its carbon footprint in a drive to drastically reduce Europe's overall carbon emissions by 2020 setting its ambitious 20/20/20 goals: cutting its annual consumption of primary energy by 20% and increase the production of renewable energy to a share of 20% by 2020 [8]. Recent initiatives gathering major IT companies started to explore the energy savings and green energy usage in network infrastructures. For example, Telefonica commits to reducing 30% its network energy consumption by 2015 [9].

In the current telecommunications networks, the vast majority of the energy consumption can be attributed to fixed line access networks. Today, access networks are mainly implemented with copper based technologies such as ADSL and VDSL whose energy consumption is very sensible to increased bitrates. The trend is to replace such technologies with mobile and fiber infrastructure which is expected to increase considerably the energy efficiency in access networks. Such ongoing replacement is moving the problem to the backbone networks where the energy consumption for IP routers is becoming a bottleneck [10][11]. In Japan it is expected that by 2015, IP routers will consume 9% of the nation's electricity [12].

In such a new environment, the development of more accurate cost models which include the energy consumption factor for both the deployment (Capex) and the maintenance (Opex) of network infrastructures is fundamental. In this paper, we discuss the most relevant energy models present in the literature highlighting possible advantages, drawbacks and utilization scenarios in order to provide the research community with an overview over the different energy characterization frameworks that are currently being employed in WDM networks.

This article is structured as follows. Section 2 introduces the energy related problems and the possible energy-efficient and energy-aware solutions. In Section 3, we illustrate the energy-aware architectures on which the energy models are currently based. Section 4 discusses the three main energy models present in the literature. Section 5 illustrates real power consumption models for router architectures with different scaling factors. In Section 6 we present our comprehensive energy model for WDM networks. Finally, Section 7 summarizes the conclusions of this article.

2 Background

Increasing the energy efficiency of the different equipment, operations or processes constituting a network infrastructure is not the ultimate solution, as argued in the Khazzoom-Brookes postulate [13]: "increased energy efficiency paradoxically tends to lead to increased energy consumption" (a phenomenon known as the Jevons Paradox or rebound effect as well). In fact, an improvement of the energy efficiency leads to a reduction of the overall costs, which causes an increase of the demand and consequently of the energy consumption overtaking hence the gained offset.

It is safe to say that a paradigm shift is required in the network in order to sustain the growing traffic rates while limiting and even decreasing the power consumption. In order to overcome the rebound effect, it is necessary to adopt the *carbon neutrality* or, when available, the *zero carbon* approach. In carbon neutrality, GHG emitted by legacy (dirty) energy sources (e.g. fossil-based plants) are compensated – hence, neutrality – by a credit system like the cap and trade or the carbon offset [14]. In the zero carbon approach, renewable (green) energy sources (e.g. sun, wind, tide) are employed and no GHG are emitted at all. Clearly, green energy sources are always preferable with respect to the dirty ones as they limit (or avoid at all) GHG emissions, although renewable sources are variable in nature and their availability may change in time. In order to reduce the energy consumptions and contain the concomitant GHG emissions in the atmosphere, the two following measures have been identified:

- *Energy efficiency:* refers to a technology designed to reduce the equipment energy consumption without affecting the performance, according to the *do more for less* paradigm. It takes into account the environmental impact of the used resources and constraints the computations to be executed taking into account the ecological and potentially the economic impact of the used resources. Such solutions are usually referred to as *eco-friendly solutions*.
- *Energy awareness:* refers to an *intelligent* technology that adapts its behavior or performance based on the current working load and on the quantity and quality of energy that the equipment is expending (*energy-feedback information*). It implies knowledge of the (dirty or green) sources of energy that supply the equipment thus differentiating how it is currently being powered. Energy-aware solutions are usually referred to as *eco-aware solutions*. A direct benefit of energy aware techniques is the removal of the Khazzoom-Brookes postulate.

To become a reality, green Internet must rely on both concepts and a new energy-oriented network architecture is required, i.e. a comprehensive solution encompassing both energy-efficient devices and energy-aware paradigms acting in a systemic approach. The definition of a proper energy model to estimate and characterize the energy consumption of a network infrastructure is hence of primary importance. Nonetheless, due to its distributed character and wide diversity in network equipment types (routers, switches, modems, line cards, etc.), a direct estimation of network equipment power consumption is notoriously difficult. Several energy models have been proposed so far which try to emulate the different network elements (NEs) in an easy and comprehensive manner.

3 Energy-Aware Architectures

Current router architectures are not *energy-aware*, in the sense that their energy consumption does not scale sensibly with the traffic load. In [15] several router architectures have been analyzed and their energy consumptions under different traffic loads have been evaluated. Results show that the energy consumption between an idle and a heavily loaded router (with 75% of offered traffic load) vary only of 3% (about 25 W on 750 W). This happens because the router line cards, which are the most power consuming elements in a router, are always powered on even if they are totally idle. On the contrary, the energy consumption decreases to just 50% if the idle line cards are physically disconnected. Such a scenario suggests that future router architectures will be energy-aware, in the sense that they will be able to automatically switch off or dynamically downclock independent subsystems (e.g. line cards, input/output ports, switching fabrics, buffers, etc.) according to the traffic loads in order to save energy whenever possible. Such energy-aware architectures are advocated both by standardization bodies and governmental programs [16] and have been assumed by various literature sources [15][17][18]. Our study will be therefore focused on such energy-aware architectures that can adapt their behavior, and so, their energy consumption, to the current traffic loads. The energy consumption of such architectures is made up of a fixed part (Φ), needed for the device to be turned on, and a variable part (ε), somehow proportional to the traffic load. It is precisely *how* the variable energy consumption scales with the traffic that differentiates the various energy models. In the following paragraphs, we present them in detail and discuss their major benefits and drawbacks. Note that in each model the power consumption starts from the fixed power consumption value Φ that represents the power necessary for the device to stay up (and idle).

4 Energy Models

Basically, three different types of energy models have been reported in the literature:

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

4.1 Analytic Energy Models

Analytic energy models [18] take into consideration a number of parameters describing the NEs and provide their energy consumption by mean of a mathematical description of the network. The challenge of analytic energy models is to abstract irrelevant details while representing essential aspects in order to obtain a realistic characterization of the network elements energy consumption. Once an analytic model has been set up, it has the ability to describe the energy consumption of NEs in virtually any possible network 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. In fact, the abstraction and the generalization are the two key points of this kind of models. 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 the real world devices as far as possible but it is not always possible to know the proprietary internal device architectures and hardware technical specifications.

In [18] the authors propose an analytic energy model in the ILP formulations for energy-efficient planning in WDM networks. They identify three types of traffic: transmitting, receiving and switching traffic, though there is no difference between electronic and optical traffic.

4.2 Experimental Energy Models

Experimental models [19][20][21][22][23] totally rely on energy consumption values of real world devices. They consider the NEs energy consumptions declared by the manufacturers or the experimentally measured values to create a map of well-known off-the-shelf working devices samples. For routers – which are the most studied NEs – the energy consumption is reported against the aggregated throughput and then the mapping is used for interpolating or extrapolating energy consumption data for routers 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 measure the energy consumption under different traffic loads, they only refer to a punctual evaluation under specific assumptions. Furthermore, the interpolation/extrapolation method is not a reliable measure of real devices energy consumption, as the devices energy consumption may vary sensibly with its technology, architecture, features and size (e.g. aggregated throughput, number of line cards, ports, wavelengths, etc.). In fact, in [19] the authors analyze power consumption of core routers based on datasheets found in [20], and conclude that for higher throughputs the routers consume more power. However, smaller routers tend to be located near the edge of the network whereas larger routers are more central in the network where the traffic is more aggregated. Therefore they consider the power consumption per bit rate. This reveals that larger routers consume less energy per bit than smaller ones. When aggregating over the entire network, the power consumption will also be the largest at the edge of the network and smaller in the centre. It is also showed how energy consumption depends on the packets size and on the bitrates of the links. Greater packets need less energy than smaller ones, due to the lower number of headers that have to be processed. In [21] 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. 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. So, an experimental model, though providing some real energy consumption values, is not enough to cope with the requirements of a comprehensive energy model.

In [22] and [23] the authors propose a mixed energy model. Network nodes 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.

4.3 Theoretical Energy Models

Theoretical models [24] are instead totally based on the theoretical predictions of the energy consumption as functions of the router size and/or the traffic load (in a way similar for the Moore's law [25] for the central processing units and the Gilder's law for the bandwidth of communication systems [26]). Such models have the benefit of being simple and clear, but the predictions may substantially differ on the long run from the real energy consumption values. Besides, it is often difficult to foreseen the NEs energy consumptions and, as they rely only on empirical data, it is not a based on any rigorous scientific model. Furthermore, both experimental and theoretical energy models do not provide detailed energy consumption of each subsystem or component, but they simply describe at high level the energy consumption at the expense of granularity and accuracy. In [24] the author proposes a simple theoretical model in which the router energy consumption grows with a polynomial function of its capacity. This estimation has been proved to be quite similar to the real energy consumption values [23].

5 Power Consumption Models

Power consumption models express the power consumption (*P*) of routers versus the offered traffic load (*L*). In power consumption models, the current absorbed power, i.e. energy per second, is plotted against the traffic load that the router is currently offering. The power consumption may be expressed through a set of concrete models whose growth behaviors are obtained either from analytical, experimental, theoretical energy models or a combination of them. In the following sections, we analyze four different models: linear, theoretical, combined and statistical power consumption models.

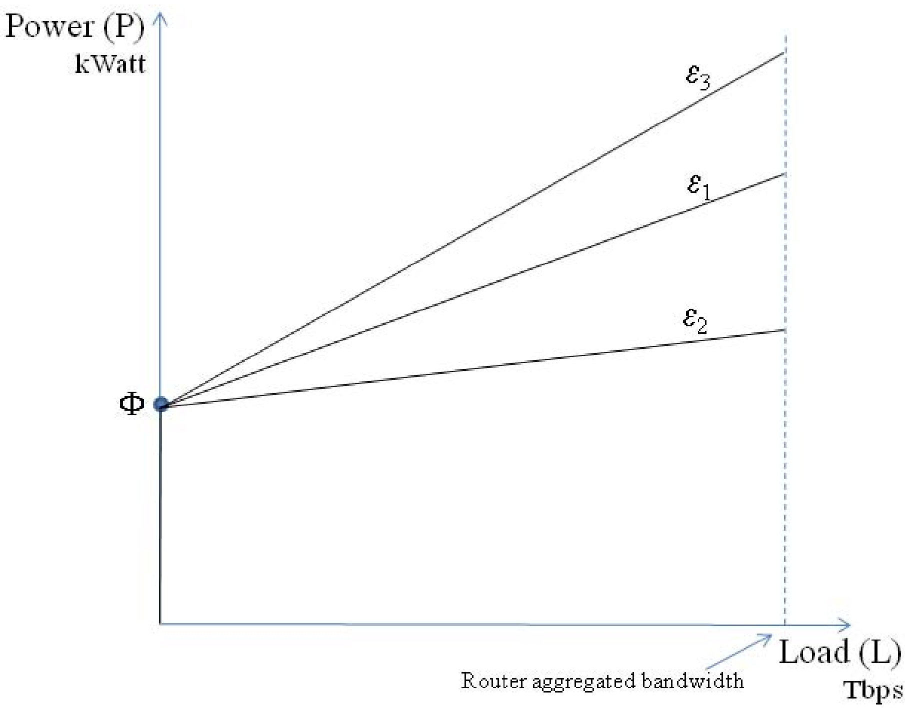

Fig. 1. Power consumption in linear power consumption model

5.1 Linear Power Consumption Models

In linear models, the power consumption scales linearly with the traffic load up to the maximum router capacity (its aggregated bandwidth). Here, routers with diverse technology and/or sizes may scale differently with the traffic: three scale factors (ε_1, ε_2, ε_3) are reported in Fig. 1.

In this model, it holds that:

$$P = \varepsilon_i \cdot L \tag{1}$$

where ε_i is a scaling factor depending on the technology and size of the router *i*. Alternatively, the diverse slopes (ε_i) may represent different traffic types (see the Section 5.4), as was assumed in [18].

This power consumption model has the benefit of being simple and easy to implement, but it has the drawback that it is not possible to upper bound the power consumption to a desired values (e.g. 2Φ, as the results in [15] suggest).

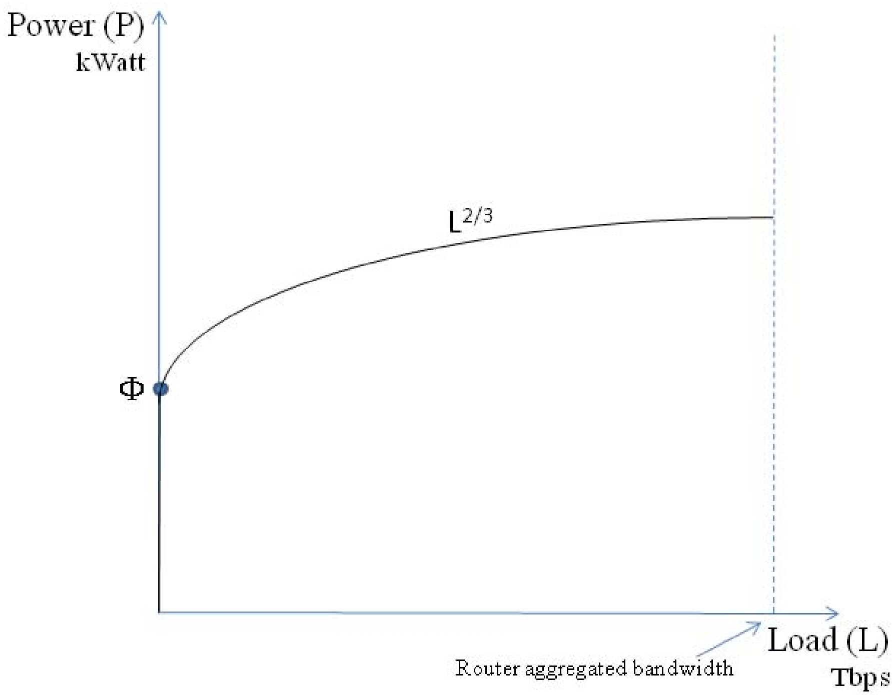

Fig. 2. Power consumption in theoretical power consumption model

5.2 Theoretical Power Consumption Models

In theoretical models, the power consumption is expressed as a function of the load that tries to follow the trend of real devices power consumption. Using a high level formula, theoretical models are usually employed to describe in a simple though effective manner the relation between the power consumption and the current traffic load. The theoretical energy model presented in [24] is the following:

$$P = C^{2/3} \tag{2}$$

which states that the router power consumption grows with a polynomial function of its capacity. Now, if we substitute the router capacity with the load, we obtain a feasible model to represent how the power consumption varies with the traffic load. Such a model has demonstrated to be quite in line with the energy consumption of some real world devices [24], and for this reason has been sometimes used in literature papers [19].

Theoretical power consumption models show an easy-of-use advantage as it suffices to substitute the router aggregate bandwidth or current traffic load to immediately get the power consumption value. No tuning of any parameter is needed (such as ε_i) and the power consumption growth rate is always well predictable. Unfortunately, such models have the same drawbacks as the theoretical energy ones (see the section 4.3).

5.3 Combined Power Consumption Models

Combined models are characterized by different power consumption scaling rates at different traffic loads. They are represented by step functions whose domain is partitioned into different traffic load intervals. Each load interval may be characterized by a different function; for example (see Fig. 3), the power consumption may scale

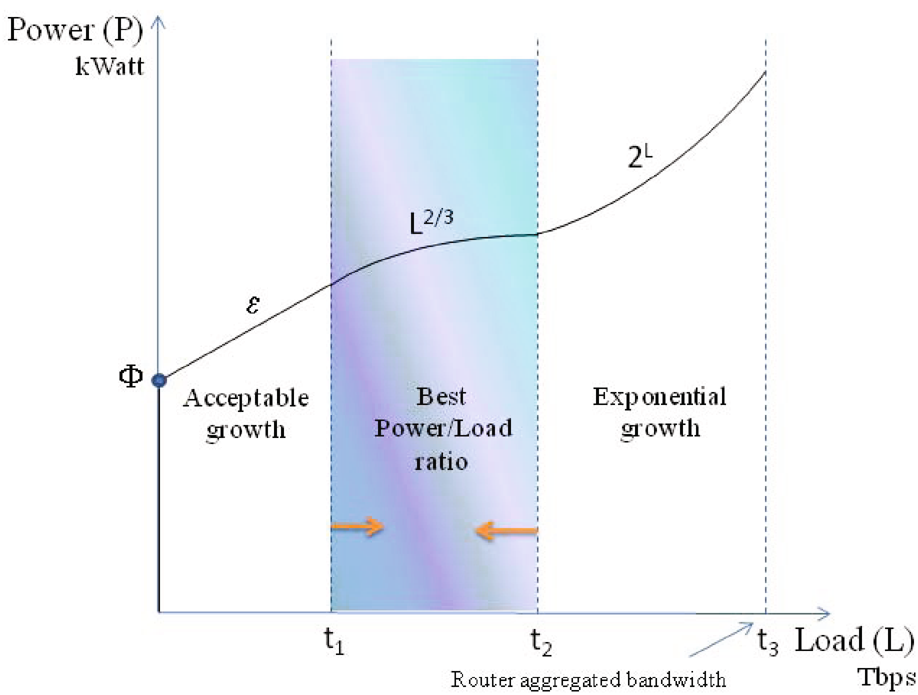

Fig. 3. Power consumption in combined power consumption model

linearly (ε) with low loads (lower than t_1), polynomially ($L^{2/3}$) at medium loads (between t_1 and t_2) and exponentially (2^L) at high loads (greater than t_2). Some or all the sub-functions may be derived from other models, as in the example.

Note that in such a model, it may be convenient to balance the traffic across the network in order to keep the router local traffic inside the acceptable zone where the energy consumption scales polynomially with the traffic load. In fact, it may be worthwhile to keep the traffic above the t_1 threshold, in order to amortize the fixed power consumption Φ, and below the t_2 threshold, to not exceed into the exponential power consumption zone (between t_2 and t_3).

Such power consumption models are pretty complete and may be used to resemble quite complex scenarios in which the network elements have complex architectures and show a known – although not linear – overall power consumption behavior. Note that, thanks to their greater complexity, such models open new perspectives on the traditional network load balancing criteria in order to save energy while achieving low connection rejection ratios. Obviously, such added values come at the expense of computational complexity and scalability.

5.4 Statistical Power Consumption Models

Statistical models consider an additional factor contributing to the energy consumption which is the traffic *type*: all optical or electronic traffic, O/E/O conversions, 3R regenerations, optical amplifications, wavelength conversions, are all examples of different traffic types that affect differently the energy consumption inside a given router. In fact, each type of traffic has in principle different power consumptions when traversing a router (either as an optical lightpath or a packet/circuit-switched electronic path), also depending on the technology and the architectural design that the router adopts. The model is defined as *statistical* because the power consumption depends at each moment on the statistical distribution of the overall traffic in the router. The more traffic of kind *i*, the more the energy consumption will depend on the scaling factor ε_i. Furthermore, each router may have its different scaling factors depending on its technology, architecture and size. For example, in Fig. 4 three different types of traffic are represented, each with its own scaling factor: electronic traffic (ε_3), optical traffic without wavelength conversion (WC) capability (ε_2), and optical traffic with WC capability (ε_1). The three types of traffic have different impacts on the overall router energy consumption, but all of them grow linearly. Note that the electronic traffic scales worse than the optical traffic, as reported in [27]. Note also that, in the example reported in Fig. 4, the three traffic types scales all linearly, even if with different slopes. Statistical models may assume that the various types of traffic scale at different growth rates, for example the electronic traffic may scale exponentially while the optical traffic with WC may scale polynomially and the optical traffic without WC may scale linearly. Furthermore, each router may have its own statistical energy model depending on its design choices in order to adapt its energy consumption behavior to different technologies and architectures.

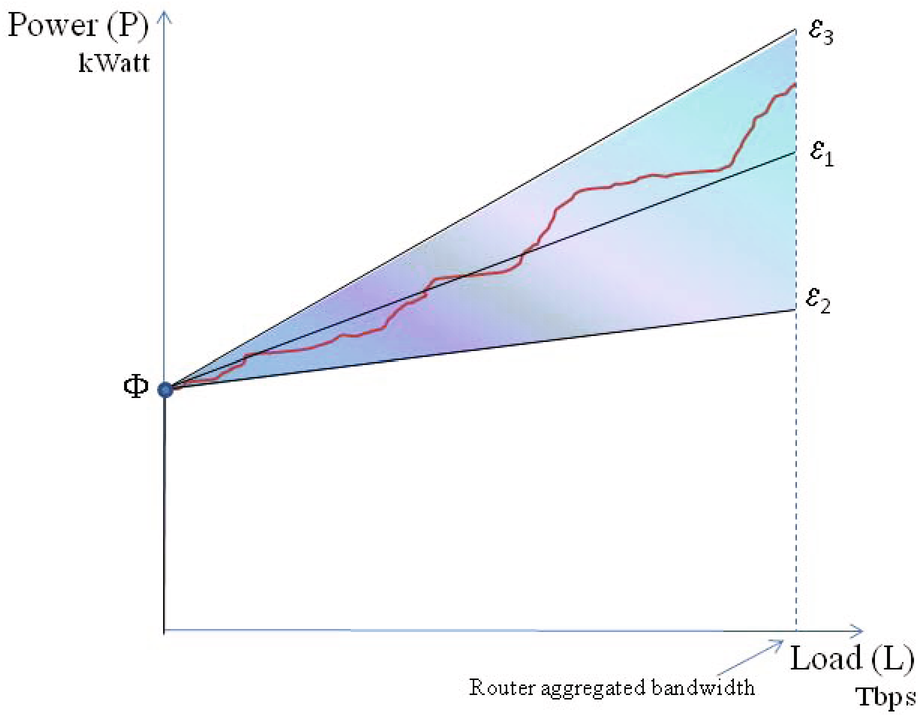

Fig. 4. Power consumption in statistical power consumption model

The statistical model is the most complete one as it allows representing a wide range of devices and power consumption behaviors depending not only on routers technology factors but also on the different traffic types.

6 A Comprehensive Energy Model for WDM Networks

In order to formally characterize the energy consumption of network elements we propose a comprehensive analytic model based on real energy consumption values and in line with the theoretical growth rate predictions encompassing new energy-aware architectures that adapt their behavior with the traffic load in order to minimize the energy consumption.

The energy model comprises three types of traffic of a WDM network:

1. Electronic traffic (with or without add/drop multiplexing, electronic wavelength conversion, 3R regeneration, etc.);
2. Optical traffic with WC;
3. Optical traffic without WC.

These types of traffic are supported by different flavors of optical and electronic network elements (router, switches, transceivers, optical fiber links and amplifiers, 3R regenerators, etc.). Power consumption of real NEs has been obtained by literary sources[15][20][23][27][28] and power consumption equations have been derived from these measurements.

Such an energy model characterizes the different components and sub-systems of the network elements involved in energy consumption. It provides the energy consumptions of network nodes and links of whatever typology and size and under any traffic load. The efforts in the developing of such an energy model have been focused on realistic energy consumption values. For this scope, the energy model has been fed with real values and the energy consumption behavior of NEs has been crafted in order to match with the state-of-the-art architectures and technologies. At this extent, future energy-efficient architectures with enhanced sleep mode features have been considered and implemented in the energy model. The energy model is based on a linear combinations of energy consumption functions derived from both experimental results [15][19][20][23][27][28] and theoretical models [22][23][24]. Besides, following the results reported in [15][16][19][28], the power consumption has been divided into a fixed and a variable part; fixed part is always present and is required just for the device to be on; variable part depends on the current traffic load

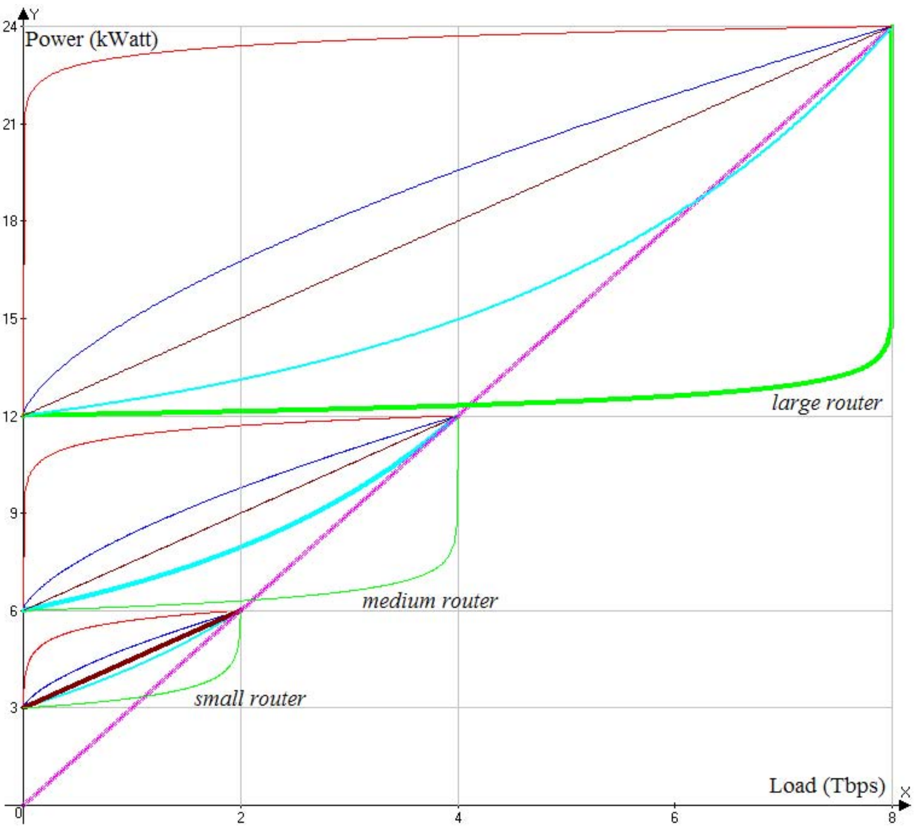

Fig. 5. Power consumption functions for various size electronic routers

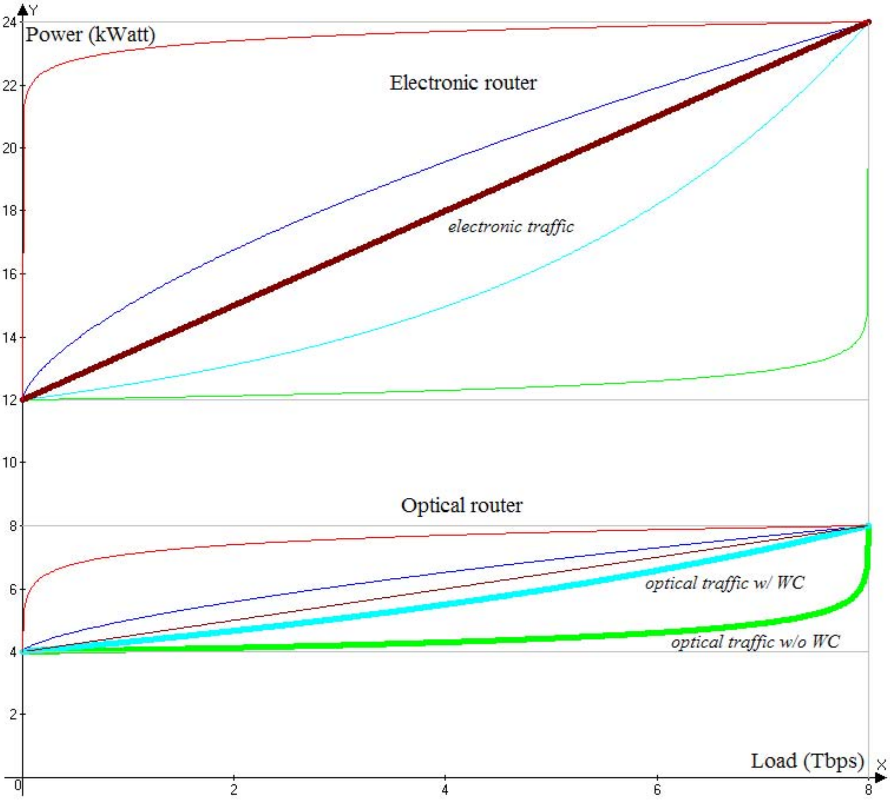

Fig. 6. Power consumption functions for electronic and optical routers

on the device and may vary according to different energy consumption functions. We chose a linear combination of two different functions (logarithmic and line functions) and weighted them with a parameter depending on both the type of traffic and the size of the NE, in order to obtain a complete gamma of values and thus adapting its behavior to the most different scenarios. In particular in our energy model we managed to obtain that larger routers consume less energy per bit than the smaller routers (see Fig. 5), as reported in [19][20], and that electronic traffic consumes more energy per bit that optical traffic (see Fig. 6), as reported in [27][28]. Wavelength conversion and 3R regenerations have a not negligible power consumption which is accounted for in the model. Finally, links have an energy consumption that depends on the length of the fiber strands and thus on the number of optical amplification and regeneration needed by the signal to reach the endpoint with an acceptable optical signal-to-noise ratio (OSNR).

The power consumption functions of three routers of different sizes are reported in Fig. 5. Each router may support different types of traffic, each defined by a different curve. In the example in figure, the thicker lines represent the power required by a given type of traffic (e.g. electronic traffic). We can observe that, according to our model, the larger the router, the larger the *total* energy consumption, as the fixed part notably contributes to (half of) the energy consumption. But if we focus only on the variable power consumptions, we observe that, for example, a traffic load of 2 Tbps, requires as much as 3 kW in the smaller router, about 1.5 kW in the medium one and just 1 kW in the larger router. In this way, we managed to obtain that greater routers consume less energy per bit than smaller ones, as reported in [19][20]. Note also that the overall energy consumption scales linearly with the size of the router and that half of the energy consumption is due to the fixed part and the other half to the variable part, according to literature source [15].

The power consumption functions of an electronic and an optical router are reported in Fig. 6 (optical router values not in scale). Three types of traffic are represented: electronic traffic in the electronic router and optical traffic with and without WC in the optical one. We observe that the electronic traffic grows quickly with respect to the optical traffic and that, among the optical traffic, the WC actually consume a not negligible quantity of energy. As the power consumption functions are obtained by linear combinations of the logarithmic and the line functions, the complete gamma of slopes can be represented by the actual curves.

7 Conclusions

The energy consumption has to be considered as an additional constraint and, given the current ICT energy consumption growth trend, it will likely represent the major constraint in the designing of WDM network infrastructures, even more than the bandwidth capacity. In order to lower the energy consumption and the concomitant GHG emissions of such infrastructures, it is necessary to assess the power consumption of current and future energy-aware architectures through extensive energy models that characterize the behaviors of the network equipment. In this paper we presented and discussed the main energy and power models currently employed in the literature and provided an overview over the different scenarios that are currently being employed in WDM networks. Finally, 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 WDM networks. The model, based on real energy consumption values, tries to collect the main benefits of the previous models while maintaining low complexity and, thus, high scalability. We believe that such an energy model will help the development of new energy-oriented networks for achieving sustainable society growth and prosperity.

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