15

Green Optical Networks: Power Savings versus Network Performance

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15.1 Introduction

With an ever-increasing demand for bandwidth, connection quality, and end-to-end interactivity, computer networks require more and more sophisticated and power-hungry technologies. This is why every network segment, that is, from the access to the core, has been targeted to find possible ways to reduce the power consumption.

The term core refers to the backbone infrastructure of a network that usually interconnects large metropolitan areas, and may span across nations and/or continents. The term access, on the other hand, refers to the so-called last mile or segment of a network where central offices (COs) and remote nodes (RNs) provide connectivity between the end users and the rest of the network infrastructure. Depending on the reach of the access segment, core and access may or may not be interconnected via a metro infrastructure.

Regardless of the network segment under exam, optical communication plays a central role in reducing the power consumption in communication networks. In the core part, transport

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solutions based on wavelength division multiplexing (WDM) technologies are able to significantly lower their overall required power levels because of their ability to limit the number of optical-electrical-optical (O-E-O) conversions per each provisioned connection. Similarly, in the access segment, Passive Optical Networks (PONs) are becoming an attractive alternative to their active counterparts. For this reason, and in order to foster further improvements, energy efficiency in the optical layer has attracted a lot of attention, and a wide range of topics are addressed in the literature.

On the other hand, all these strategies developed to reducing the power drained by the optical layer mainly resort to techniques that turn off unused devices. These techniques can be enabled by the introduction of a sleep mode option in the equipment. However, performing these operations while, at the same time, making sure that other network parameters (e.g., delay, quality of transmission, blocking ratio, reliability) are not affected, requires careful design and/or provisioning operations.

This chapter aims at exploring and evaluating these trade-offs in more detail and to provide a different insight into the green design and provisioning problem in optical networks. More specifically, Section 15.2 presents an overview of the power consumption performance of the main components used in optical access and core networks together with their options in terms of potential power savings. Section 15.3 concentrates on the trade-off between energy efficiency and delay in optical access networks, providing a case study based on WDM optical passive networks. Section 15.4 focuses on green WDM core networks. Three specific trade-offs are analyzed in terms of energy saving versus (i) connection blocking probability (Section 15.4.1), (ii) quality of transmission of the optical signal (Section 15.4.2), and (iii) reliability levels of the provisioned optical connections.

The presented results point out how it is important during the design and provisioning phase not to concentrate on power minimization only. The risk would be to end up with an optical network where the potential savings coming from lower power consumption levels may be nullified by poor performances in terms of other crucial quality of service parameters.

15.2 Device-Specific Energy Characteristics

Access networks are responsible for nearly three quarters of the power consumption of all network equipment [1]. On the other hand, the average utilization of access network components is lower than 15%, allowing some room for energy saving mechanisms. Power optimization can be performed at the device and subdevice levels (see also the techniques described in Section 15.3). The devices responsible for most of the energy consumption are at the end points of each access connection, that is, the optical network unit (ONU) at the user premises and the optical line terminal (OLT) in the CO. There are also some other devices (e.g., splitter, and (possibly) switches) used at intermediate points, but this depends on the specific access architecture under exam. In the case of a PON only optical splitters are used, and they do not require any power for their operations. In the case of an Active Optical (access) Network (AON), or point-to-point (PtP) fiber solutions some switching operation might be included, thus requiring extra power consumption. The list of the typical active optical access network devices together with their energy consumption is presented in Table 15.1.

In core networks, the number of devices is lower compared to the access segment [1]. On the other hand their power consumption value is higher. In addition, it is expected that once end users are able to benefit from connectivity rates in the order of Gbps, the core part of the

Table 15.1 Power consumption values of optical access network equipment

Device	Power consumption [W]	Source
Optical network unit (ONU)	5	[2]
Optical line terminal (OLT)	2/port	[2]
Fiber switch (if needed)	1.5/port	[2]

Table 15.2 Power consumption values of optical core network equipment

Device	Power consumption [W]	Source
OTN 10G transponder	20	[3]
OTN 40G transponder	160	[3]
OTN 100G transponder	360	[3]
Wavelength selective switch (WSS)	60	[3]
Optical demultiplexer	40	[3]
EDFA amplifier	8–16	[3]
Wavelength Cross Connect (WXC)	25	[3]

network will be required to handle a huge amount of traffic with obvious consequences in terms of power consumption. In core networks there are different types of devices for which power consumption can be the subject of optimization. They are listed in Table 15.2 together with their power consumption.

In order to optimize their energy usage access and core network devices can be switched off or put into a low power consumption mode when they are not used. The difference in how and when these options are used lies mainly in the time required to take a device back to a fully operational state. If switching on/off operations can be scheduled ahead of time, then a component can be completely switched off without any fear that it will not be ready when needed. If, on the other hand, a device might become essential at a moment's notice, then it might not be completely switched off, but only some of its components may enter a low power consuming state.

Take, for example, a typical transponder (used not only in core networks but also in OLTs and ONUs). Its components used for receiving are a photodiode, a transimpedance amplifier (TIA), an analog to digital converter (ADC) block, a digital signal processing (DSP) unit, and a deframer. For transmitting, on the other hand, a transponder needs a laser with thermoelectric cooler, a modulator, and a framer. In addition, a transponder normally includes a forward error correction module and some Layer 2 (L2) and/or Layer 3 (L3) electronics. In order to save energy the components responsible for transmission/reception (e.g., the lasers, DSP, ADC, and the modulator) may be switched off or put into a low power mode. However, since the transition from low power mode to the operational mode is not immediate and requires a certain time to be performed, this should be done carefully. On the other hand, it will be easier to activate/deactivate the L2 or L3 electronic. Depending on the components' characteristics different energy saving algorithms can be proposed, but their implementation will trigger a number of performance trade-offs that has to be considered. These aspects are addressed in detail in the rest of the chapter.

15.3 Energy Saving for Optical Access Networks Based on WDM PONs

There are many studies aimed at improving the energy efficiency in access networks and in particular targeting PONs. This is mainly due to the large number of active devices deployed at the user premises. These green approaches can be grouped according to the layer that they target, that is, physical layer (i.e., including hardware) energy-efficient techniques (e.g., component integration or low power circuits), data link layer power optimization strategies (e.g., cyclic sleep) as well as hybrid energy-efficient approaches that work on more than one layer at the same time [4–8]. When focusing on data link layer solutions, the techniques that can be used in PONs include power shedding, dozing, and deep/fast sleep modes, [5, 9]. There are also a number of software-based solutions that can be used to lower the power consumption in PONs, for example, adaptive link rate, traffic shaping, and wavelength shutdown [8].

According to the power shedding concept, the ONU and/or the OLT go into a low power mode by putting only a subset of its components (e.g., Ethernet interface) into sleep mode while keeping both transmitter (Tx) and receiver (Rx) active. The purpose is to not introduce any additional transmission delays (e.g., for wake-up procedures and/or synchronization) in the case of any upcoming upstream and/or downstream traffic. As a result, only a limited amount of power can be saved.

With deep and fast sleep approaches, the Tx and the Rx at the ONU/OLT are in sleep mode when they are not in use (e.g., no upstream/downstream traffic from/to a specific ONU/OLT). This technique can achieve the best energy savings, but a synchronization phase is required to make sure that the OLT/ONU is aware that the transceiver on the other side is active. In addition, the length of the sleep period has a direct impact on packet delay, and as long as the TX is asleep, packets have to be either queued or dropped. Usually, a fast sleep technique is combined with some sleeping policies to optimize the energy savings performance, for example, cyclic sleep [6].

Dozing is a compromise between the advantages of shedding (i.e., little impact on the transmission delay) and the energy saving performance achievable by deep and fast sleep. According to the dozing concept, only the Tx is put into sleep mode while the Rx stays always on (this can be applied at the ONU and at the OLT in the case of WDM-based PONs). One of the main challenges with a dozing approach is to know when to put the Tx into sleep mode and when to wake it up in the presence of incoming traffic. The most straightforward way would be to wake up the Tx as soon as there is traffic to be sent and to put the Tx into sleep mode right after the transmission phase is over. This scheme is referred to as immediate wake-up. It is characterized by a delay that is due to the transition time between sleep and active states. However, this transition also leads to an energy overhead [10], which is paid every time the Tx changes operative state. One way to overcome this drawback is to wait for a certain time (i.e., T_{maxq}), with the intent to collect a number of packets before transmitting them all together in a burst. In this way the number of transitions is minimized, but at the expense of an additional delay. Such a scheme raises the question for "acceptable" delays, especially in the presence of possible delay guarantee requirements for specific services.

The trade-off between energy reduction and delay performance can be addressed by means of schemes that are able to keep the transmitter in a sleep state as long as possible (i.e., to achieve higher energy savings) but are also intelligent enough to wake it up in time to assure the transmission of the collected packets without breaching their maximum delay constraints. This

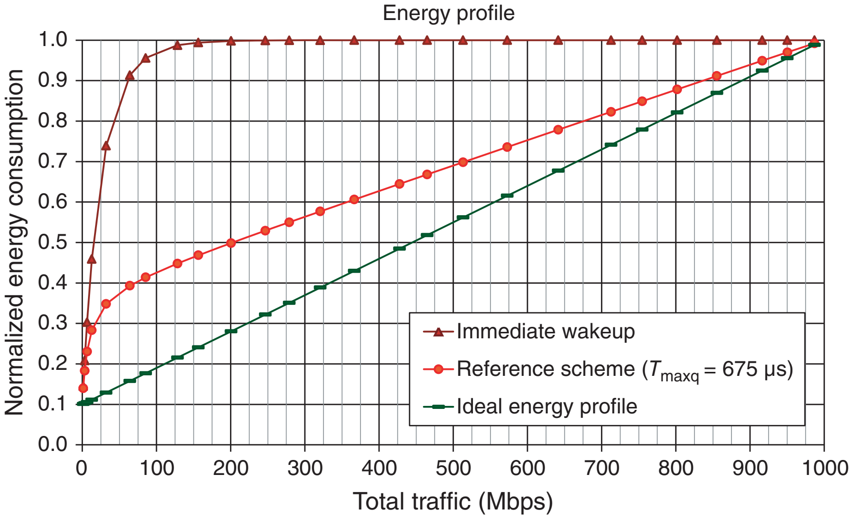


Figure 15.1 Energy profile of Tx

wake-up time calculation takes under consideration the maximum traffic delay constraint, the (nonnegligible) transition time between sleep and active states, the propagation delay (between ONU and OLT), and the transmission delay of all packets waiting for transmission.

The trade-off of energy consumption and packet delay of this scheme is presented in Figures 15.1 and 15.2. More details about the assumptions and the simulation setup are available in Ref. [11]. One conclusion from both figures is that an immediate wake-up scheme has the best delay performance but it is able to offer energy savings only for low link loads, that is, lower than 15% of link occupancy. That is due to the high frequency of transmitter wake-up for nearly each packet. On the other hand, as soon as packets are collected and transmitted in bursts ($T_{maxq} > 0$) significant energy savings can be achieved in medium load conditions. The average and maximum packet delay rises but can be controlled by adapting the value of T_{maxq} to maximum delay constraint for the specific service under exam, as described in Ref. [11].

Additional energy savings can be achieved using the same "burst-formation" intuition but changing the other in which packets are transmitted, on the basis of their priority levels, that is, how stringent their maximum delay constraint is. In fact, low-priority packets, that is, with higher delay tolerance, allow longer sleep times of the transmitter and therefore offer additional energy savings. On the other hand, a high-priority packet can trigger an earlier transmitter wake-up and can be scheduled first. This information can then be incorporated into the packet scheduling operations to maximize the sleep time of the transmitter [11]. Figure 15.3 presents the energy savings that can be observed for traffic composed of two traffic classes: high-priority class and low-priority class with maximum delay restriction of 1 ms and 5 ms, respectively. The scheme with traffic class differentiation can further improve energy savings compared to the previously explained bursting scenario, in particular for traffic with low portion of high-priority packets (Figure 15.4).

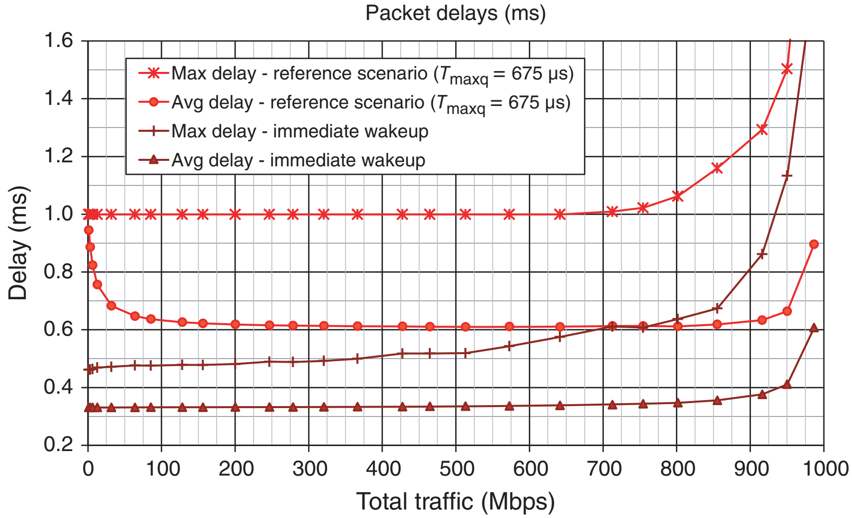


Figure 15.2 Packet delays

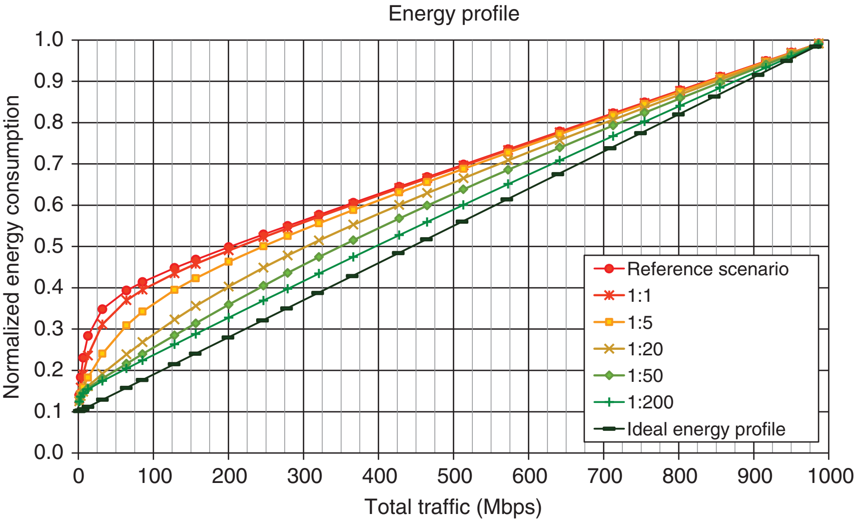


Figure 15.3 Energy profiles when exploiting traffic diversity

15.4 Energy Saving for WDM Core Networks

Transparent optical core networks are a power efficient option, able to reduce the energy consumption of the transport infrastructure. The energy consumption of optical core networks can be further reduced by a proper network design [12–17] and by green routing approaches (as elaborated in Chapter 13) where the (energy) savings come from the minimization of the

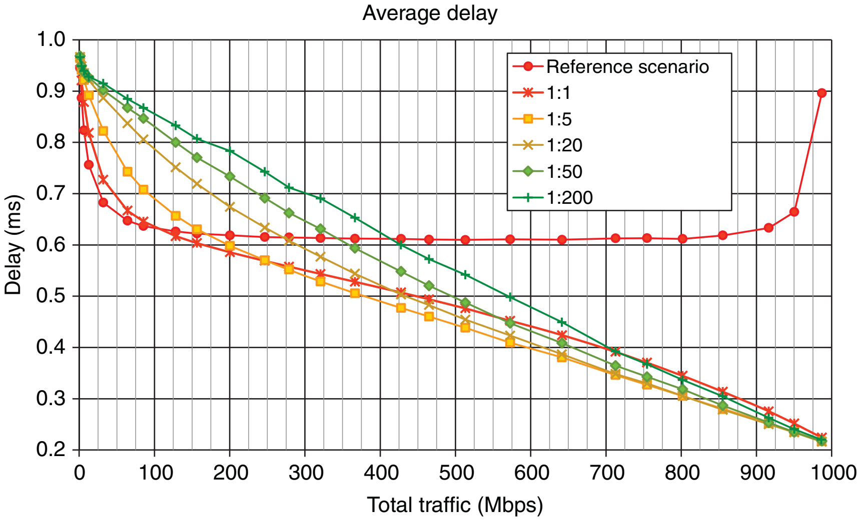


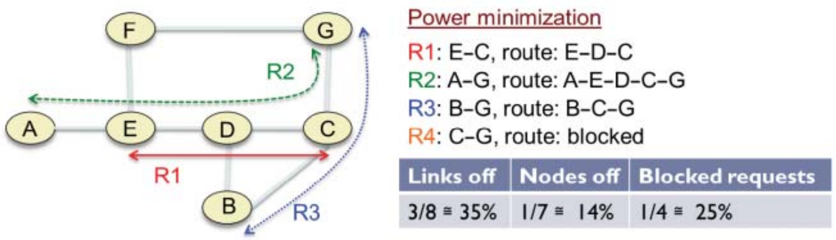
Figure 15.4 Average high-priority packet delays when exploiting traffic diversity

number of active network elements that need to be powered on in order to guarantee the required connectivity. These methods are based on temporarily setting unused network elements in a power saving (*sleep*) mode. However, the minimization of energy consumption may have a negative impact on other network performance metrics, which should be carefully assessed in order to guarantee the practical usefulness of a certain energy saving approach. The next sections look carefully into this problem by addressing a number of trade-offs between energy saving levels and important network metric such as blocking probability, quality of transmission (QoT), and reliability levels.

15.4.1 Energy Saving versus Blocking Probability in Transparent WDM Core Networks

The basic services provided by WDM networks are high speed and all-optical end-to-end channels, also referred to as *lightpaths*. Lightpaths are dynamically created between node pairs to both provide the desired network connectivity and accommodate arriving traffic demands. Each lightpath that needs to be created in a WDM network is assigned both a route and a wavelength – this is, the so-called routing and wavelength assignment (RWA) problem. When traffic demands dynamically enter and depart from the network, the problem is referred to as the *online* RWA problem. One of the online RWA problem objectives is to reserve the minimum number of network resources (wavelengths) for each arriving traffic demand. It is expected that by minimizing the amount of reserved resources per arriving demand, the blocking probability is reduced – where a demand is *blocked* when it cannot be created because of the lack of available wavelengths in the network.

This section explores the trade-off between energy savings and lightpath request blocking. In order to illustrate this trade-off we discuss a simple example, which is shown in Figures 15.5 and 15.6. In this example a given number of lightpaths need to be dynamically provisioned in

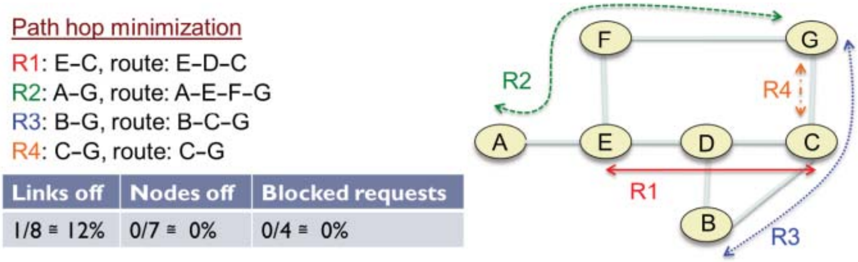


Power minimization

R1: E–C, route: E–D–C
R2: A–G, route: A–E–D–C–G
R3: B–G, route: B–C–G
R4: C–G, route: blocked

Links off	Nodes off	Blocked requests
3/8 ≡ 35%	1/7 ≡ 14%	1/4 ≡ 25%

Figure 15.5 Power versus blocking, a trade-off example: power minimization strategy



Path hop minimization

R1: E–C, route: E–D–C
R2: A–G, route: A–E–F–G
R3: B–G, route: B–C–G
R4: C–G, route: C–G

Links off	Nodes off	Blocked requests
1/8 ≡ 12%	0/7 ≡ 0%	0/4 ≡ 0%

Figure 15.6 Power versus blocking, a trade-off example: path hop minimization strategy

a WDM network with seven nodes and eight bidirectional fiber links. It is assumed to have one fiber link in each direction, with two wavelengths per fiber and equal energy consumption values for all links, that is, for simplicity we consider links with the same length, making the minimum length path problem equivalent to the minimum number of hops. Two provisioning strategies are considered: the first one focuses on finding a solution requiring the minimum amount of power (Figure 15.5), while the second one concentrates on finding the route with the minimum number of hops (Figure 15.6). The provisioning strategy with the objective to minimize the energy consumption will select the path that requires the minimum number of new network elements to be turned on, that is, by forcing the consecutive lightpath requests (R1–R4) to choose links already in use in order to avoid powering on additional network equipment. Hence, in an attempt to reduce power consumption the allocated paths become on average longer, possibly creating bottlenecks in the network, for example, link C-G is soon out of resources, making it impossible to provision connection R4.

On the other hand, the objective of a conventional, that is, not power-aware, RWA algorithm (Figure 15.6), is to balance the network resource utilization in order to minimize the blocking probability.

In the example it is shown that the power minimization strategy is able to save 35% and 14% of the energy consumed by fiber links and network nodes, respectively, at the expense of having to block 25% of the connection requests (Figure 15.5). On the other hand, considering the same traffic, the provisioning strategy based on the minimum number of hops is able to save only 12% of energy consumed by the fiber links, but it will not block any lightpath request (Figure 15.6).

This trade-off can be assessed formally by means of a Weighted Power-Aware Optical Routing (WPA-OR) strategy [18]. WPA-OR is based on a modified version of the k-shortest path algorithm [14], where each fiber link l in the network is assigned a weight (C_l) equal to:

$$C_l = \begin{cases} \alpha \cdot P_{\text{link},l}, & \text{fiber link } l \text{ in use} \\ P_{\text{link},l}, & \text{fiber link } l \text{ not in use} \end{cases},$$

where $P_{\text{link},l}$ represents the power necessary to operate the in-line power amplifier(s) along fiber link l, and α is a weighting factor with values between 0 and 1. Note that $\alpha = 0$ corresponds to a pure power minimization approach, while values of α close to 1 force to provision lightpath requests along shorter routes. Tables 15.3 and 15.4 present a trade-off between the level of energy savings and the blocking probability.

The results are obtained by simulation considering the COST 239 network topology [19], which is a Pan-European test network topology that comprises 11 nodes and 26 bidirectional links. More details about the experimental setup are available at Ref. [18]. For any given value of the load, the average power per request is defined as the ratio between the total network power consumption and the number of provisioned connection requests. The average power saved per request is computed as the difference between the total network power consumption obtained when $\alpha = 1$ and the total network power consumption for any other given value of α. The tables show that considerable power savings (up to 50%) can be achieved, but at the expense of a relevant increase in the network blocking probability.

It is obvious that power efficiency and network blocking probability are two conflicting objectives, because paths obtained by applying a pure power-aware provisioning are typically longer than the shortest possible paths, which leads to network resources fragmentation and an increased blocking probability. This can be avoided by jointly considering power minimization and resource blocking in a single cost function.

15.4.2 Energy Savings versus Quality of Transmission in WDM Core Network Design

Despite the high number of energy-efficient strategies for WDM network design [20], considering static [12] and dynamic [21, 22] provisioning, there is an important aspect of the power minimization problem in transparent WDM networks that is not always properly addressed. The absence of signal regeneration, that is, reamplification, reshaping, and retiming of the optical signal also known as 3R [23] (with its benefits in terms of reduced power consumption), has an impact on the optical signal quality at the receiver because Physical Layer Impairments (PLIs) degrade the signal quality along an optical connection.

PLIs can be divided into linear and nonlinear impairments. Linear impairments do not depend on the signal power and affect each wavelength channel individually. In contrast, nonlinear impairments such as Cross Phase Modulation (XPM) and Four Wave Mixing (FWM) can cause disturbance and interference among channels traversing the same fiber link. Usually, these physical phenomena are accounted during the RWA phase, that is, impairment aware RWA (IA-RWA) strategies [24, 25] aim at minimizing the impact of PLIs on the established connections.

Ignoring the quality of the optical signal while minimizing the power consumption might have detrimental effects on the overall network performance. In fact, energy minimization

Table 15.3 Average power saved per request (%) as a function of the network load and α

	Load [Erlang]												
	15	45	75	105	135	165	195	225	255	285	315	345	375
$\alpha = 1.00$	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
$\alpha = 0.75$	9.7%	16.9%	17.9%	16.6%	14.8%	11.3%	9.3%	6.8%	4.8%	2.6%	1.0%	0.3%	0.2%
$\alpha = 0.66$	13.7%	30.8%	31.0%	26.3%	22.0%	15.6%	12.2%	8.8%	6.5%	4.0%	2.1%	0.9%	0.2%
$\alpha = 0.50$	21.0%	40.6%	39.3%	32.9%	27.5%	19.5%	15.0%	11.4%	8.6%	5.5%	2.9%	1.3%	0.4%
$\alpha = 0.33$	27.6%	45.2%	42.5%	36.1%	31.0%	23.0%	18.5%	14.0%	10.3%	7.4%	4.1%	2.5%	1.3%
$\alpha = 0.10$	38.6%	48.5%	44.0%	39.1%	33.9%	27.4%	22.4%	17.1%	13.5%	10.4%	7.0%	4.1%	2.8%
$\alpha = 0.0001$	40.2%	49.0%	45.6%	40.0%	35.4%	28.9%	24.0%	18.8%	14.9%	11.9%	8.8%	6.6%	4.3%

Table 15.4 Blocking probability as a function of the network load and α

	Load [Erlang]												
	15	45	75	105	135	165	195	225	255	285	315	345	375
$\alpha = 1.00$						0.0000	0.0000	0.0007	0.0033	0.0095	0.0207	0.0382	0.0623
$\alpha = 0.75$						0.0000	0.0002	0.0012	0.0043	0.0103	0.0226	0.0389	0.0624
$\alpha = 0.66$					0.0000	0.0002	0.0006	0.0019	0.0058	0.0131	0.0251	0.0413	0.0631
$\alpha = 0.50$				0.0001	0.0002	0.0005	0.0014	0.0037	0.0089	0.0175	0.0277	0.0432	0.0657
$\alpha = 0.33$			0.0002	0.0006	0.0021	0.0045	0.0086	0.0140	0.0189	0.0269	0.0350	0.0513	0.0724
$\alpha = 0.10$		0.0006	0.0045	0.0092	0.0178	0.0307	0.0415	0.0518	0.0623	0.0710	0.0773	0.0863	0.1032
$\alpha = 0.0001$	0.0001	0.0077	0.0173	0.0297	0.0438	0.0519	0.0750	0.0819	0.0930	0.1017	0.1207	0.1292	0.1308

and maximization of the number of connections with their optical signal quality above a certain threshold can be considered as two conflicting objectives. This is mainly because of the way energy minimization provisioning techniques work. Most of the energy efficient RWA approaches tend to concentrate (i.e., "pack") provisioned connection requests on few links to allow as many resources as possible to enter a standby/sleep state. As a consequence, these energy-efficient RWA strategies may result in (i) longer routes on average for established connections, and (ii) higher utilization of the active fiber links, that is, the average number of used wavelength channels per fiber link being higher compared to a conventional (not energy-efficient) RWA approach. Longer paths, on the other hand, translate into worse attenuation levels, and denser fiber links result in higher XPM and cross talk levels. For these reasons, RWA strategies focusing solely on energy efficiency perform insufficiently with respect to signal quality guaranties.

The negative effects of PLI on the optical signal while performing a green WDM design may be limited by introducing regeneration at intermediate nodes inside the network [23, 24]. The idea is to trade higher power consumption values from regeneration operations at selected nodes for a better overall signal quality. Another alternative is to develop a combined impairment and energy-aware RWA approach [26], which already considers the impact of PLIs while solving the RWA problem encountering additional constraints, that is, in addition to the power minimization ones.

The PLI of a connection can be quantified by using the quality factor Q. The Q factor can be computed using the expression in Ref. [25] that includes the effects of amplification noise, the combined effects of optical filtering, XPM, and FWM. The Q factor function in Ref. [25], however, is not linear, and therefore, adding the Q factor to an RWA mathematical formulation entails nonlinear constraints, which need to be added. To avoid nonlinearity, while aiming to provide a model that accurately computes the Q factor in an Integer Linear Programming (ILP) formulation, three main techniques can be used:

- Path precomputation: as linear impairments depend only on the length of the route of the optical connections, the use of arc-path-based ILP formulations, where a set of routes are precomputed, allows for precomputing linear impairments associated to each route.
- Worst case assumption: XPM is the dominant nonlinear effect and its impact is magnitudes larger than FWM [27]. Therefore, FWM can be precomputed assuming a worst-case value (i.e., using a conservative approach) and considered as a fixed penalty for each link.
- Statistical XPM model: the statistical linear model presented in Ref. [28] allows for the estimation of the XPM noise variance, making it usable in an RWA ILP formulation

Compared to existing impairment aware RWA (IA-RWA) and energy-aware (EA-RWA) schemes, it can be shown that a combined energy and impairment aware RWA (EIA-RWA) approach provides energy consumption reduction close to that obtained by EA-RWA, but it still guarantees a sufficient level of the optical signal quality.

Figure 15.7 presents a comparison in terms of three different metrics: (a) power consumption, (b) number of active links, and (c) connections exceeding a predefined Bit Error Rate (BER) threshold, that is, the most common metric used to assess the optical signal quality of a lightpath. Results were obtained by running an ILP solver [29] on a 16-node and 23-link optical topology [30]. Each set of results is generated for three different BER thresholds (i.e., BER-th: 1E-9, 1E-11, and 1E-13) to represent lightpaths that require high, very high, and

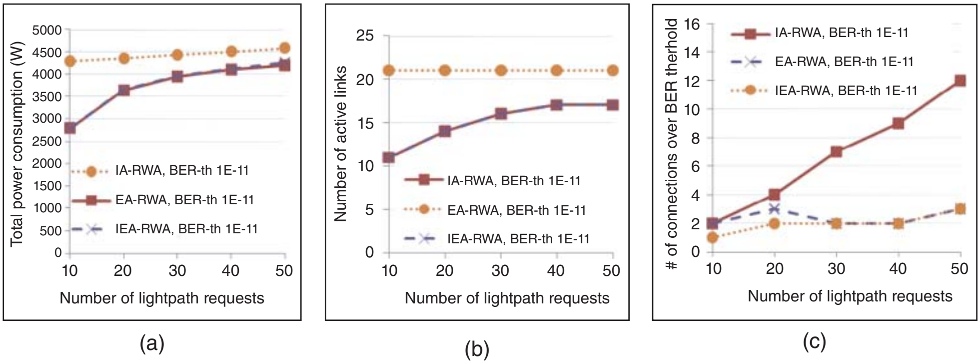


Figure 15.7 Comparison of RWA approaches

extremely high transmission quality, respectively. In terms of Q factor values, the considered BER thresholds translate into Q_{thres} of approximately 6, 6.7, and 7.3. More details on the ILP formulation, the power consumption model as well as on the experimental setup and assumptions are available at [26].

It is clear from Figure 15.7 that both EA-RWA and IEA-RWA achieve the same reduction in total power consumption (ranging from 7% up to 35%) as the IA-RWA approach. In terms of the number of used fiber links (see Figure 15.7(b)), both energy-aware approaches (i.e., EIA-RWA and EA-RWA) use the same amount. IA-RWA, on the other hand, activates every fiber link in the network, in order to minimize the number of requests above the BER threshold. The reason is that IA-RWA tends to choose short routes to minimize the effect of linear impairments, and it encourages the assignment of wavelengths that are spread around in the optical spectrum to avoid nonlinear ones. Finally, Figure 15.7(c) shows how combining energy and impairments objectives in the IEA-RWA approach provides signal quality levels that are very close to the ones provided by the IA-RWA approach while minimizing power consumption. In contrast, EA-RWA performs relatively poorly in terms of the number of lightpaths that satisfy their optical signal quality requirements.

In summary, it is important to have an approach that combines the concept of impairment and energy awareness while designing a WDM network. The reason is that minimizing energy may result in drastic signal degradation as a consequence of reducing the number of active links and thus increasing the average load per link. Conversely, considering only signal quality optimization may result in wasting large amount of energy. Connections are spread among different links to minimize the link load that increases the number of active resources in the network. By contrast, an IEA-RWA approach proves to be able to reduce significantly the power consumption levels (almost reaching the optimum level given by the EA-RWA approach) while providing the required minimum signal quality nearly equivalent to IA-RWA levels.

15.4.3 Energy Saving versus Resource Utilization in Green and Resilient Core Network Design

Resiliency to device failures is a fundamental requirement in WDM core networks. It can be achieved by installing or reserving redundant resources that will be used only in the case of a failure to restore the affected connections. Such resources are typically maintained in an active state, independent of the failure pattern, and thus consume power even when they are not utilized.

The energy efficiency of survivable WDM networks can be improved by using various techniques. One solution consists in planning or operating the WDM network in such a way that the power consumption is minimized, in addition to (or instead of) minimizing the resource installation or utilization [14, 31, 32].

Additional improvement can be achieved by enabling a sleep mode state in network equipment [14, 33]. Sleep mode represents a low power, inactive state from which devices can rapidly wake up when necessary. As redundant resources are unused until a failure occurs they can be set in sleep mode, provided that each connection of Service Level Agreement (SLA) can still be satisfied, that is, resource in sleep mode can be back in operation mode within certain time limits. A proper planning [14, 31, 32] and management [34] of the WDM network is required to support sleep mode. Indeed, devices can be put to sleep mode when they support only protection connections. The problem of planning a WDM network supporting sleep mode has been investigated extensively in the literature. Some works look into ways to improve the energy efficiency in all-optical WDM networks with dedicated path protection [14, 32], while others investigate dedicated and shared path protection schemes that can be used in IP-over-WDM networks [31].

Further improvement can be achieved by selecting an energy-efficient protection technique. An example is given by shared path protection that is known to require fewer resources than dedicated path protection, hence leading to energy savings. In the presence of shared protection, additional savings in resource usage and thus in energy can be achieved by enabling differentiated reliability (DiR) levels, which are guaranteed to the provisioned connection requests [35, 36]. If DiR is enabled, the protection path is not always available for each possible link failure scenario, which results in a significant reduction of the number of used network resources (i.e., wavelength) and thus power consumption. A proper selection of the protection resources is fundamental for the effectiveness of the protection technique with the requested reliability level, in order to enable energy savings.

The energy saving techniques for survivable WDM networks discussed above can also be combined to achieve even higher energy efficiency. The impact of three different techniques is assessed [36] using a dynamic WDM network represented by a Pan-European topology with 11 nodes and 26 bidirectional links (i.e., COST 239 [19]) where shared path protection is used. Demands are assumed to arrive randomly at the network nodes and they must be served as they are received. Each demand consists of one lightpath that needs to be provisioned between two nodes with a given level of reliability that needs to be satisfied. A demand is blocked when resources are insufficient for setting up the lightpath with the requested level of reliability. The reliability level is modeled in terms of maximum conditional failure probability (MCFP) that represents the maximum acceptable probability that the connection will not survive when a link failure occurs.

A power minimization (PM) or a resource minimization (RM) strategy is used to solve the RWA problem for the working and protection path of each lightpath connection request. The PM strategy solves the RWA problem giving priority to the power consumption values of the devices and their operational state, that is, active or sleep. The RM strategy, on the other hand, focuses only on the minimization of the number of wavelength resources used to provision each working and protection path. For each request, the working and protection paths are selected

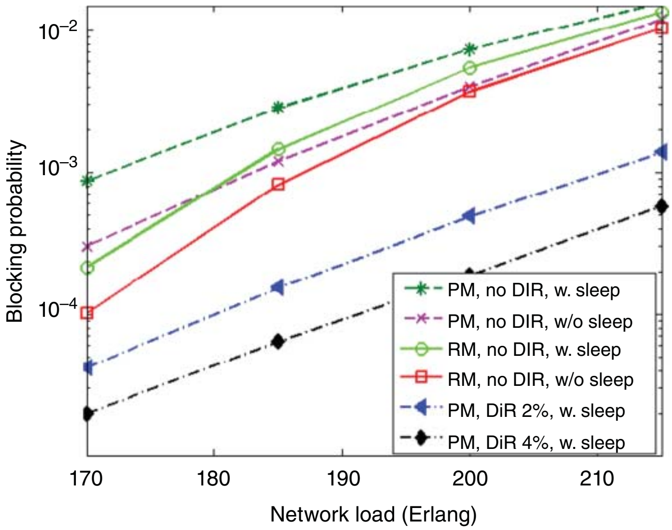


Figure 15.8 Blocking probability versus offered network load when minimizing power consumption and resource utilization

among a list of precomputed paths, according to the PM or the RM strategy, while ensuring the required level of reliability, that is, MCFP. Details of the PM and RM routing strategies and the power consumption model as well as of the experimental setup and assumptions are available at [36].

Figure 15.8 shows the blocking probability versus network load for PM and RM routing strategies. PM blocking probability performance is not as good as RM especially at low loads when the impact of blocking probability performance is less detrimental. The impact of the sleep mode and DiR are also assessed. Two insights can be gained. First, the blocking probability slightly increased when enabling sleep mode. The reason is that, for the working lightpaths, in the presence of sleep mode the cost function forces the selection of longer paths. In turn, this strategy allows setting as much as possible resources in sleep mode. This approach leads to a higher resource utilization and consequently higher blocking. On the other hand, an improvement of more than one order of magnitude in blocking probability can be achieved when a lower reliability level is requested. However, if the reliability level is further decreased (i.e., passing from 2% to 4% MCFP), only a marginal improvement in blocking probability can be achieved.

The average power savings of the different energy-efficient techniques are depicted in Figure 15.9. The PM strategy enables savings of up to 10% compared to the RM strategy, while additional savings up to 10% can be gained at low loads because of the sleep mode. However, these benefits decrease at high loads. More significant power savings, almost independent of the load, are gained by exploiting DiR. The maximum of about 25% is achieved by jointly optimizing power consumption and resource utilization while enabling DiR and sleep mode.

In summary, energy-aware strategies help to save power at different loads but higher blocking probability especially at low loads. This trade-off between network performance

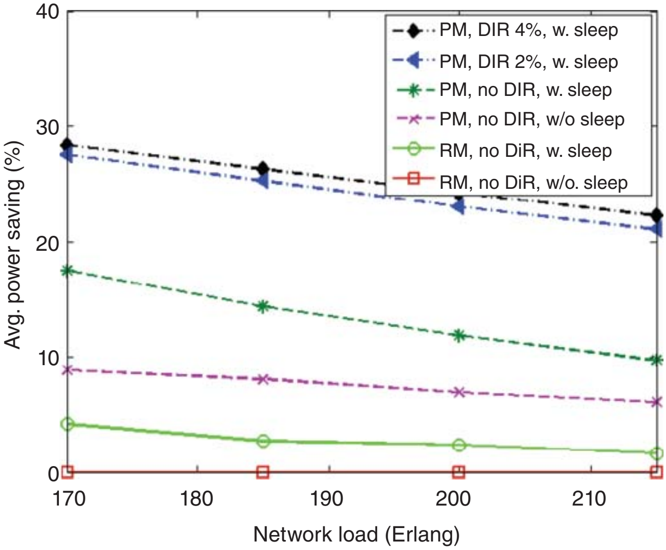


Figure 15.9 Average power saving versus offered network load

and power savings exists also when introducing a sleep mode, which is energy efficient at low loads but increases the blocking probability. On the contrary, DiR may effectively provide energy efficiency, while introducing significantly less blocking probability, independent of the load. The combined effects of the three different energy-efficient techniques can lead to energy savings of up to 25% while improving the blocking probability compared to a conventional protection techniques.

15.5 Summary

Although it is obvious that optical networks are a promising alternative to reduce the power consumption of telecommunication networks, energy can be further saved by proper power-aware network design and/or connection provisioning approaches. While investigating the various aspects of green optical networks this chapter showed how power minimization and some important network performance parameters (i.e., delay, connection blocking probability, lightpath quality of transmission, and connection reliability levels) are in conflict. The reason lies either in the length of the provisioned paths originating from a pure power-aware provisioning approach or in the devices transition times required to go from a low power to a fully functional operational state. The presented results highlight this crucial aspect of the green optical networking optimization problem and show how it can be mitigated by carefully balancing the importance of the objective functions to be optimized.

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