Designing Power-Efficient WDM Ring Networks

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Abstract. Traditionally, optical networks have been designed with the objective of minimizing the capital expenditure (CAPEX) without considering the operative costs (OPEX), due for instance to energy consumption. However, the increase of energy consumption and corresponding costs and the challenges imposed by the environmental issues (such as the global warming and the limited oil reserves) are demanding for a more responsible energy usage, including in the optical networking field.

The paper discusses how the mandate of saving energy can be included into the network design process. Power-saving design of WDM metro rings with traffic grooming capabilities is presented and compared against CAPEX-optimized designs. Considerations on the power efficiency and cost efficiency of different ring architectures are derived.

Keywords: optical network design, traffic grooming, power saving, unidirectional WDM ring.

1 Introduction

Metro networks require a careful planning in order to aggregate the traffic of the different types of services (e.g., grid services, voice) and to reduce the costs. In the past years, planning of optical network has always aimed at selecting the minimum amount of resources to support the requested traffic demands, i.e., at minimizing the equipment and installation costs, also known as capital expenditures (CAPEX). Operative costs (OPEX) – in particular the costs for powering the optical and electronic equipment – have been always overlooked and considered marginal by network providers. However, a reconsideration of the validity of these assumptions is required for the increase of energy costs [1, 11] and for environmental issues [9].

Pioneering studies on the evaluation of the energy consumption of optical network equipment were carried out by Tucker and Butler. Their works include thorough studies on the power consumption of optical and electronic switching systems [2, 12] and the comparison between different technologies [13]. Subsequent works have focused on IP routers [6, 7], and discussed power consumption

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issues and possible savings. However, these initial works are restricted to single systems (i.e., node) or few interconnected systems. Subsequent studies have considered the power consumption of all-optical networks [3, 8] and multi-layer optical networks [3, 5, 10] and provided precious considerations on how to improve the network power efficiency.

In this paper, the power consumption is accounted during the design of WDM metro networks with unidirectional ring topology. Three architectural designs with different degrees of optical transparency and traffic grooming capabilities are considered [4]. In the first generation (FG) architecture, every node electronically processes and aggregates all the incoming connection traffic, including the in-transit traffic. In the single hop (SH) architecture, every node electronically processes only traffic that is inserted into or extracted from the network at that node, i.e., wavelength connections, or lightpaths, bypass transparently the intermediate optical nodes. The (hybrid) multi-hop (MH) architecture makes use of both lightpaths and electronic traffic grooming that is performed at few selected intermediate nodes.

The paper presents a model that quantifies the network power consumption at the optical layer, at the electronic layer and at their interfaces. Such model is included into the design of the three architectures. The main objective of the work is to address the open questions about 1) whether the design of a network at minimum CAPEX is equivalent to a design at minimum OPEX (i.e., power consumption), and 2) whether the CAPEX-efficient architectures are also OPEX-efficient.

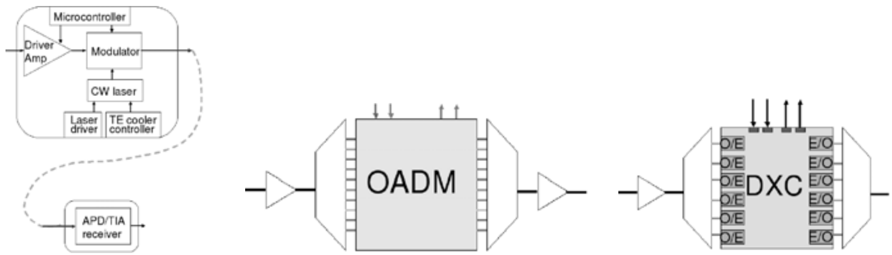
To address these open questions, the design of a unidirectional WDM ring, based on either a FG, SH, or MH architecture, is OPEX-optimized and compared against the CAPEX-optimized design, for increasing rate of the traffic demands and various scenarios of power consumption in the optical and electronic layers. The comparison between CAPEX-optimized and OPEX-optimized designs and among the different architectural designs will help to derive useful considerations on designing power-efficient WDM rings.

2 Power Budget Model

To operate a multi-layer optical network, power needs to be supplied to each layer (i.e., the optical layer and the electronic layer) and to the interface between the two layers (i.e., for electrical-optical and optical-electrical conversion). At the different layers and at their interfaces, a number of factors influence the power consumption and the most relevant are: the emploied technology, the design of the systems, and the operating conditions. In order to derive a power budget model, a brief discussion on the three different contributions to the power consumption and on the made assumptions is carried out next.

2.1 Powering the E/O and O/E Interfaces

Electrical-optical (E/O) and optical-electrical (O/E) interfaces are transmitters and receivers, that, respectively, convert the electronic signal into optical signal



(a) Transmitter and receiver architecture (b) Optical add-drop multiplexer (OADM) architecture (c) Digital cross-connect (DXC) architecture

Fig. 1. Network equipment for the E/O and O/E interfaces (a), at the optical layer (b), and at the electrical layer (c)

and vice-versa. Usually, transmitters (Fig. 1(a)) consist of a laser, a modulator, a laser driver, and a thermo-electric (TE) cooler. While power efficiency of a laser is typically very high (i.e., the power consumption is as the one at the optical layer), the modulator and the laser driver may drain the most of the power within the transmitter [2]. The receivers (Fig. 1(a)) consist of a photodiode followed by a trans-impedence amplifier (TIA), whose power consumption is non-negligible.

Since a transmitter and a receiver is required for each lightpath to be established, the overall power drained by the various components of the transmitters and receivers can be accounted on a per-lightpath basis.

2.2 Powering the Optical Layer

The optical signal transmission is affected by power losses and by linear and non-linear impairments. Power losses decreases exponentially the transmitted power in function of the distance, making the signal amplification or regeneration necessary. The power consumed by the amplifiers is accounted by assuming that amplifiers are required and present at the nodes operating at the optical layer. In the following, the impact of linear and non-linear physical impairments is neglected[1].

The optical signal bypasses transparently the nodes operating at the optical layer, i.e., the nodes equipped with an add-drop multiplexer (OADM) (Fig. 1(b)). An OADM is based on a wavelength selective switch fabric and requires wavelength multiplexers and demultiplexers and line power amplifiers. Power to be supplied to the OADM nodes is assumed to be directly proportional to the number of OADM ports, i.e., to the passing-by lightpaths and locally added/dropped lightpaths. The overall power for the optical layer, i.e., for operating the OADM and the amplifiers, is therefore considered proportional to the number of OADM ports.

[1] Power consumption for compensation of linear and non-linear impairments (e.g., for dispersion compensation) can be easily accounted by aggregating its amount to the power consumption of the amplifiers or the E/O (O/E) interfaces.

2.3 Powering the Electronic Layer

The electronic layer (e.g., based on IP/MPLS or other technologies) is responsible for processing the data and aggregating the traffic. The process is taking place at the digital cross-connect (DXC) (Fig. 1(c)). Power consumption of a DXC is considered directly proportional to the number of input and output DXC ports, i.e., line terminating equipment and local tributary interfaces.

3 Network Architecture Design

Based on the equipment described above, the problem of designing a WDM ring can be formulated as follows. Given a unidirectional ring topology and the traffic rate of the demands to be supported, the purpose of the design problem is to select the set of lightpaths that are necessary to carry the offered traffic demands. (The routing of the traffic demands is predetermined by the unidirectional ring topology.) The set of lightpaths determine the equipment to be installed (e.g., number of transmitters and receivers, number of DXC and OADM ports) and thus the power that the network will consume.

The optimal design from the CAPEX perspective is the design at minimum equipment installation cost. Typical objective functions for CAPEX-optimal solutions are the minimization of the wavelength cost and/or the minimization of the E/O and O/E interfaces costs [4].

The optimal design from the OPEX perspective (i.e., power consumption) is the design that requires the minimum amount of power to operate the network. The objective function for an OPEX-optimized design can defined according to the power budget model explained in Section 2.

Next, the design problem at minimum CAPEX or at minimum OPEX are discussed for the three considered architectures.

3.1 First Generation (FG) Design

In FG ring networks, nodes are equipped with DXC only. FG ring design consists of lightpaths that are established between physically adjacent nodes. Traffic grooming is performed at each node.

Optimal design at minimum CAPEX can be obtained in polynomial time [4]. The optimal design at minimum CAPEX is also an optimal design at minimum OPEX (i.e., power consumption), for the proposed power budget model.

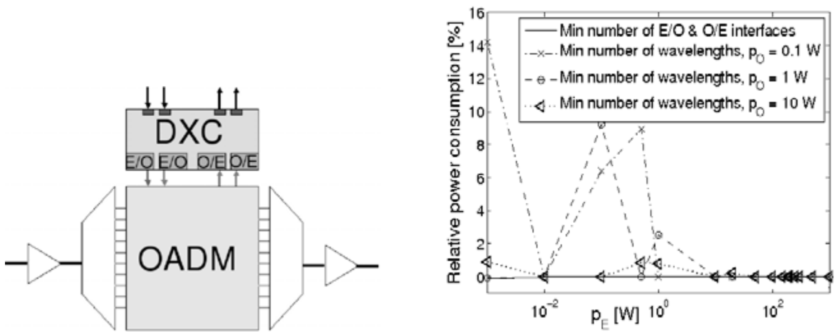
3.2 Single-Hop (SH) Design

In SH ring networks, nodes are equipped with OADM only. SH ring design consists of tributary signals that are transmitted using a single lightpath, i.e., all-optically from the source to the destination with a single (optical) hop. Traffic grooming between tributary signals that belong to distinct traffic demands, i.e., distinct node pairs, is not possible.

Optimal design at minimum CAPEX can be obtained in polynomial time [4]. The optimal design at minimum CAPEX is also an optimal design at minimum OPEX (i.e., power consumption), for the proposed power budget model.

3.3 Multi-Hop (MH) Design

In MH ring networks, the nodes are equipped with hybrid add-drop multiplexers (HADM), which consists of an OADM and DXC as shown in Fig. 2(a). In the OADM, lightpaths can be transparently transmitted, added or dropped. Traffic of the dropped lightpaths can be aggregated in the DXC, along with the local traffic. Therefore, in a MH network, the traffic is transmitted using a concatenation of lightpaths, thus requiring multiple optical hops. Designing a MH network aims at finding the set of lightpaths and thus the nodes at which the traffic must undergo optical-electrical-optical conversion.



(a) HADM (b) Relative power consumption

Fig. 2. MH architecture: HADM node (a), relative power consumption [%] vs. p_E for different designs at minimum OPEX among those at minimum CAPEX (b)

Optimal design at minimum CAPEX is NP-hard problem. Heuristic algorithms and linear programming (LP) formulations are available [4]. In [4], MH design is shown to be cost-effective with respect to SH and FG architectures when either the wavelength cost or the interface cost or their joint cost is used as minimization function. This cost-effectiveness is achieved thanks to the possibility to exploit the optical transparency in the OADMs and traffic grooming capabilities in the DXCs.

Optimal design at minimum OPEX is also NP-hard problem. The relation between the CAPEX-optimized design and the OPEX-optimized design is discussed next on a case study.

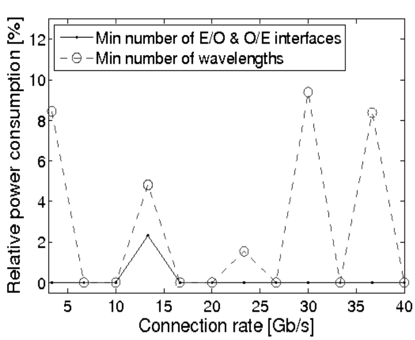
4 Results

This section presents and compares the power required by the various WDM ring architectures, optimally designed for CAPEX or OPEX minimization. Numerical results are optimally found by a commercially available LP solver, under the following assumptions. The unidirectional ring consists of 6 nodes. Transmission rate of lightpaths is 40 Gb/s. The matrix of traffic demands is complete and uniform. Unless otherwise stated, the rate of traffic demands is 10 Gb/s. Power required for E/O and O/E interfaces of each lightpath is 5 W, as quantified in [2] for commercial products operating at 40 Gb/s.

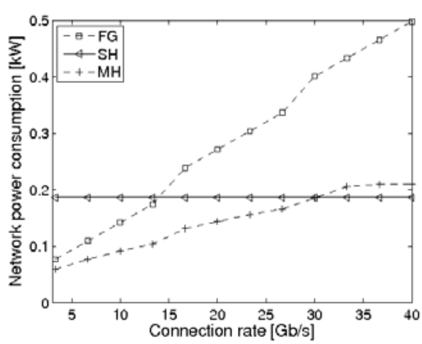
Let p_E indicate the power consumption of the electrical layer per DXC port. Let p_O indicate the power consumption of the optical layer per OADM port. The network power consumption is thus expressed as function of p_E and p_O and includes also the power required for E/O and O/E interfaces.

As indicated in Section 2, a CAPEX-optimal design of SH ring or a FG ring is also an OPEX-optimal design. Fig. 2(b) quantifies the additional power (in percentage) required in a CAPEX-optimal MH ring with respect to the OPEX-optimal MH ring, for different values of p_E and p_O. Two objective functions for CAPEX minimization are considered: minimization of the maximum number of lightpaths on a link and minimization of the number of E/O and O/E interfaces. Among the CAPEX-optimal solutions, the one at minimum OPEX is then selected. The figure shows that neglecting the OPEX in the planning may lead to an increase of OPEX costs, that in some cases, may be 14 % or even higher. This happens when the objective is the minimization of the maximum number of lightpaths on a link and for low values of p_E and p_O. This finding is also confirmed when the rate of traffic demands varies, as shown in Fig. 3(a) for $p_E = p_O = 200$ mW and for rates between 3 and 40 Gb/s.

Figs. 3(b)-4(b) compare the power consumption of the OPEX-optimal design in FG, SH, and MH rings. Fig. 3(b) quantifies the power consumption versus the rate of each traffic demand, when $p_E = p_O = 200$ mW. For such rates, SH architecture requires always one lightpath for each connection. Thus, power consumption is independent from the load. In FG and MH architectures, power consumption increases with the rate as a large number of lightpaths is required.

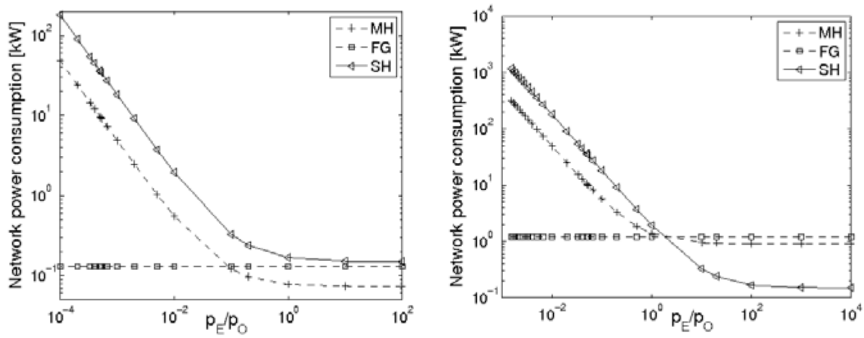


(a) Relative power consumption in MH



(b) Network power consumption

Fig. 3. Power consumption vs. rate: designs at minimum OPEX among those at minimum CAPEX, for MH (a), designs at minimum OPEX for FG, SH, and MH (b)



(a) $p_E = 0.1$ W (b) $p_E = 10$ W

Fig. 4. Network power consumption vs. p_E/p_O for $p_E = 0.1$ W (a) and $p_E = 10$ W (b)

The break-even point between FG and SH indicates that the use of just optics may save power at high load, i.e., when traffic grooming may not help to further reduce the resources utilization and, thus, the drained power.

Figs. 4(a) and 4(b) quantify the power consumption versus the ratio of p_E/p_O, when $p_E = 0.1$ W and 10 W, respectively. When p_O decreases (i.e., the ratio increases), MH may drain less power than FG, because it can exploit the power-efficient optical layer. However, for such values of p_O, if p_E is also high (Fig. 4(b)), SH is more power-efficient than MH. This controversial result is due to the more complex node architecture (i.e., HADM) in MH networks, consisting of both DXC and OADM. This leads to power consumption for both the electronic and the optical layer components, yielding a higher overall power consumption.

5 Conclusion

The paper discussed the problem of accounting the OPEX, due to equipment power consumption, during the design of optical networks with traffic grooming capabilities. A power budget model that accounts for power dissipation at the optical layer, electrical layer, and E/O and O/E interfaces was proposed and applied to the design of a unidirectional WDM ring with first-generation, single-hop, or multi-hop architecture.

While, in general, the design at minimal CAPEX is also at minimal OPEX in SH and FG networks, this may not hold anymore in MH networks. It was found that an OPEX-oblivious design may require up to more than 14% additional power.

When optimizing the OPEX, the most power-efficient architecture depends on the power consumption of the different layers and their interfaces. Interestingly, MH architecture that is known to be most CAPEX-efficient [4] may not be the most OPEX-efficient. MH is more flexible and can exploit optical transparency and traffic grooming capabilities at the nodes. But, the increased flexibility may require a more complex node architecture that, in turn, drains more power.

These results permit to derive also insightful guidelines for reducing the power consumption in optical networks, e.g., utilization of node architectures that are more power-efficient and can provide optical transparency and traffic grooming capabilities, introduction of innovative node architectures that, for instance, can selectively switch-off components (i.e., the DXC or the OADM in an HADM), study of innovative network designs that exploit the power-efficient equipment.

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