Design of Green Optical Networks with Signal Quality Guarantee

Cicek Cavdar, Marc Ruiz, Paolo Monti, Luis Velasco, and Lena Wosinska

Abstract— **Energy consumption of communication networks is growing very fast due to the rapidly increasing traffic demand. Consequently, design of green communication networks gained a lot of attention. In this paper we focus on optical Wavelength Division Multiplexing (WDM) networks, able to support this growing traffic demand. Several energy-aware routing and wavelength assignment (EA-RWA) techniques have been proposed for WDM networks in order to minimize their operational cost. These techniques aim at minimizing the number of active links by packing the traffic as much as possible, thus avoiding the use of lightly loaded links. As a result, EA-RWA techniques may lead to longer routes and to a high utilization on some specific links. This has a detrimental effect on the signal quality of the optical connections, i.e., lightpaths. In this study we quantify the impact of power consumption minimization on the optical signal quality. and address this problem by proposing a combined impairment and energy-aware RWA (IEA-RWA) approach. Towards this goal we developed a complete mathematical model that incorporates both linear and non-linear physical impairments together with an energy efficiency objective. The IEA-RWA problem is formulized as a Mixed Integer Linear Programming (MILP) model where both energy efficiency and signal quality considerations are jointly optimized. By comparing the proposed IEA-RWA approach with existing RWA (IA-RWA and EA-RWA) schemes, we demonstrate that our solution allows for a reduction of energy consumption close to the one obtained by EA-RWA approaches, while still guaranteeing a sufficient level of the optical signal quality.**

Index Terms— **Physical Impairments, energy-efficient networks, optical WDM networks.**

I. INTRODUCTION

THERE is a rising concern about the energy consumption figures of communication networks [1]. For this reason every network segment, i.e., from the access to the core, has been the target of optimization studies aimed at reducing power consumption. One important result that was found for core networks is the possibility to considerably reduce power consumption by relying on optical transmission technologies [2]. In fact, transmission in the optical layer allows for a transparent flow of data from source to destination without the need for any opto-electrical-opto (O-E-O) conversion, with an evident gain in terms of energy consumption. For this reason, in order to make 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. Energy-efficient strategies for network design [3] as well as for static [4] and for dynamic [5], [6] provisioning have been proposed to minimize the power necessary to support the traffic demands. Similar studies addressed also the issue of the power consumed by the provisioned protection resources [7]-0.

Nevertheless, there is one important aspect in the power minimization problem in Wavelength Division Multiplexing (WDM) networks that seems to be not fully addressed yet. The ability of the optical layer to transparently transmit data is undoubtedly efficient in saving energy, but the absence of O-E-O conversion has an impact on the optical signal quality at the receiver, i.e., physical layer impairments (PLI) degrade the signal quality along an optical path (lightpath).

PLI can be divided into linear and non-linear impairments [10]. Linear impairments such as Amplified Spontaneous Emission (ASE) noise, Group Velocity Dispersion (GVD), and Polarization Mode Dispersion (PMD), do not depend on the signal power and affect each wavelength channel individually. In contrast, non-linear impairments such as Self Phase Modulation (SPM), Cross Phase Modulation (XPM), and Four Wave Mixing (FWM) affect not only each wavelength channel individually but also their effect can cause disturbance and interference among channels traversing the same fiber link. Usually these physical phenomena are accounted for during the routing and wavelength assignment (RWA) phase, i.e., by using impairment aware RWA (IA-RWA) strategies [10] whose aim is to minimize the number of connections affected by the physical impairments.

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 and impairment satisfaction rate maximization (i.e., maximization of the number of connections with signal quality above a certain threshold) can be considered as two conflicting objectives. This is mainly due to the way energy minimization techniques work. Most of the energy efficient RWA approaches "pack" the lightpaths as much as possible in order to reduce the number of lightly loaded network elements and to put as many resources as possible into a stand-by/sleep state. As a consequence, these RWA strategies may result in (1) longer routes, used to pack lightpaths on the minimum number of active fiber links, and (2) higher utilization of the (active) fiber links, i.e., the average number of used

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wavelength channels in the fiber links is higher when compared to a conventional (not energy-efficient) RWA approach.

For these reasons the RWA strategies focusing solely on energy-efficiency perform poorly in respect to signal quality guaranties solutions. Longer paths translate into worse attenuation levels, and denser fiber links result in higher XPM and cross talk levels. The authors in [11] look into the relation between power consumption and the physical network design problem and present some initial tradeoff results between impairment satisfaction rate and energy levels. Their contribution addresses the fiber deployment and optical devices placement problem while, to the best of the authors knowledge, no RWA strategies have been proposed so far in the literature to tackle the joint energy and PLI problem.

In this paper a signal quality guaranteed energy-aware RWA solution is presented for the first time and a comprehensive impairment and energy aware RWA (IEA-RWA) framework is proposed. A complete mathematical model is devised by incorporating both linear and non-linear physical impairments. The problem is formulized as a Mixed Integer Linear Programming (MILP) model where both energy efficiency and signal quality considerations are jointly optimized. This is made possible by the unique nature of the proposed MILP formulation which is able to account for, in a linearized form, the impact of linear and non linear optical impairment as a constraint. The impairment calculation is based on the statistical model presented in [12]. Different levels of signal quality guarantee are considered, i.e., 1E-9, 1E-11, and 1E-13. These signal quality levels were chosen based on available IP traffic measurements [13], [14]. The illustrative numerical results confirm the existence of a tradeoff between energy minimization and impairment satisfaction rate maximization and show that via the proposed multi-objective provisioning strategy it is possible to minimize the power consumption of a WDM network while still guaranteeing the desired level of signal quality.

II. IMPAIRMENT MODEL

The PLI of a lightpath can be quantified by using the quality factor *Q*. We consider a *Q*-factor expression (see [15] for details), which includes effects of ASE noise, the combined effects of SPM/GVD and optical filtering, XPM, and FWM. In this work, we extend that model to include also the power penalty due to PMD. ASE, FWM, and XPM are calculated assuming that they follow a Gaussian distribution. The combined effects of SPM/GVD and optical filtering are quantified through an eye closure metric calculated on the most degraded bit-pattern. The power penalty due to PMD is obtained considering the length of the lightpath, the bit rate and the fiber PMD parameter. Based on these assumptions the *Q*-factor of a lightpath is calculated according to

$$Q = \frac{pen_{eye} \cdot P_{transmitter}}{pen_{PMD} \cdot \sqrt{\sigma^2_{ASE} + \sigma^2_{XPM} + \sigma^2_{FWM}}} \tag{1}$$

where $P_{transmitter}$ denotes the transmitted signal power, pen_{eye} denotes the relative eye closure penalty attributed to the effects of SPM/GVD and optical filtering, and pen_{PMD} is the power penalty due to PMD. Finally, σ^2_{ASE}, σ^2_{XPM}, and σ^2_{FWM} denote the electrical variance of ASE noise, XPM, and FWM, respectively. A detailed analytical expression of each term in eq. (1) can be found in [15].

In view of eq. (1), adding the *Q*-factor to a RWA formulation entails non-linear constraints to be added. To avoid all these non-linearities and to aim at providing a model that accurately computes the *Q*-factor in an ILP formulation we propose a statistical-based *Q* model consisting in three main techniques: pre-computation, worst case assumption, and statistical model.

Since linear impairments depend only on the length of the route of the optical connections, the use of arc-path-based formulations [16] (where a set of routes is pre-computed for each traffic demand) allows linear impairments associated to each route to be also pre-computed. This is the case of pen_{eye}, pen_{PMD} and σ^2_{ASE} that become constant parameters. Nonetheless, the specific values of σ^2_{XPM} and σ^2_{FWM} for each optical connection depend on the route and the wavelength assignment. Notwithstanding, XPM is the dominant effect, being the value of the XPM variance several times greater than one of FWM. To illustrate this, let us consider, for example, a path over the 16-node network in [17] with a Q-factor of 7.3 (Bit Error Rate (BER) ≈ 1.44E-13). Under the assumption of a medium-loaded scenario defined by a blocking probability lower than 1%, the values of variance of XPM and FWM are 1.58E-4 and 5.66E-6 respectively. It can be seen that the XPM variance is more than 27 times larger than FWM variance. For this reason, we consider a *worst case* approach for FWM, which consists of pre-computed fixed penalties for each link assuming a fully loaded system. Although this approach introduces *Q* overestimation it can be proved that the overestimation is negligible. Finally, regarding XPM we use the statistical linear model presented in [12] which allows for the estimation of the XPM noise variance, making it usable in a RWA ILP formulation.

More specifically, the XPM model takes advantage of the additive property of σ^2_{XPM}, deduced from the mathematical expressions presented in [18], [19]. For the sake of clarity, equation (2) reproduces this property. Let *E* be the set of optical links and *W* be the ascending frequency ordered set of wavelengths (each one associated with an optical channel labeled from 1 to |*W*|). Let $\sigma^2_{XPM}(r,\lambda)$ represent the value of XPM variance for a lightpath using route *r* and wavelength *λ*. Additionally, let $\sigma^2_{XPM}(e,\lambda,i)$ be the XPM noise variance on the reference channel *λ* as a consequence of channel *i* in link $e \in E$. Finally, δ_{ei} indicates whether wavelength channel *i* of link *e* is busy or not.

$$\sigma^2_{XPM}(r,\lambda) = \sum_{e\in r}\sum_{\substack{i\in W \\ i\neq\lambda}} \delta_{ei} \cdot \sigma^2_{XPM}(e,\lambda,i) \tag{2}$$

As introduced above, a model consisting in a set of continuous linear functions of *λ* to estimate $\sigma^2_{XPM}(e,\lambda,i)$ ($s^2_{XPM}(e,\lambda,i)$), one for each wavelength channel *i*, was presented in [12]. Every linear function in the model consists of a set of connected linear segments defined by two parameters: a slope and a range of wavelengths. Each of these parameters is estimated by functions of the number of link amplifiers. From an exhaustive model validation, we concluded in [12] that Q values computed using that XPM linear model accurately match the ones obtained with analytical XPM expression in [19]. Additionally, the linearity of the model, allows it to be included in RWA ILP formulations.

III. IMPAIRMENT AND ENERGY-AWARE RWA PROBLEM FORMULATION

The impairment and energy-aware RWA (IEA-RWA) problem is a specific case of static RWA problem where a set of traffic demands are simultaneously routed over a given physical topology. In addition to the basic RWA problem formulation, constraints computing the quality of the lightpaths in terms of Q-factor are defined and power consumption of the network is calculated and incorporated. Regarding the objective function, the power consumption and the signal quality of the optical connections are jointly minimized in order to reduce the total cost of the solution. Thus, we define the off-line IEA-RWA problem as follows:

Given:

- a physical topology G(N,E), where N represents the set of nodes and E the set of fiber links, with a set of wavelengths (W) supported on each link.
- a set of demands D, characterized by the source and destination nodes.
- BER threshold requirement for each connection request in the network.

Output:

- a route and wavelength assignment for each demand.

Objective: minimize both the energy required to provision all the demands and the number of lightpaths below the equivalent Q threshold (i.e., above BER threshold). The BER threshold is used as a measure of the signal quality target so to maximize the number of lightpaths with the signal quality guarantee according to this threshold.

To solve the IEA-RWA problem, we present an arc-path based ILP formulation where linear impairments and FWM-worst-case are pre-computed beforehand. Aiming at adapting our impairment model to be included in the ILP, equations (3), (4), and (5) represent a reformulated version of the Q expression in eq. (1) where $A(r)$ and $B(r)$ contain those terms that can be generated as input data of the ILP problem.

$$Q = \frac{A(r)}{\sqrt{B(r) + \sigma^2_{XPM}(r, \lambda)}} \tag{3}$$

$$A(r) = \frac{pen_{eye}(r) \cdot P_{transmitter}}{pen_{PMD}(r)} \tag{4}$$

$$B(r) = \sigma^2_{ASE}(r) + \sigma^2_{FWM} \tag{5}$$

From equation (3) and given a certain route r and the required Q threshold (Q^{thres}) of a demand, we define the corresponding XPM threshold (XPM^{thres}) as the maximum amount of XPM noise variance that the lightpath could admit without violating the Q threshold. More formally, it can be defined as follows:

$$XPM^{thres}(r) = \left(\frac{A(r)}{Q^{thres}}\right)^2 - B(r) \tag{6}$$

Therefore, constraints are added in the IEA-RWA ILP for counting whether a demand is routed ensuring the required BER threshold or not by comparing the XPM of the obtained lightpath with the XPM threshold. Note that the XPM threshold of a demand varies depending on the chosen route due to the linear impairments associated to it. This threshold is compared with the value obtained using the XPM linear model presented in [12]. It is worth mentioning that when a route and a wavelength assignment are found ensuring the required XPM threshold, the sufficient BER level or the equivalent Q threshold is also guaranteed without the need for any post-processing computation.

The following notation is used for the sets and the parameters:

N	Set of nodes of the network, index n.
E	Set of links of the network, index e.
W	Set of wavelengths, index w.
D	Set of demands, index d.
$R(d)$	Set of routes of demand d, index r.
t_{dre}	Equal to 1 if the route r of the demand d contains the link e.
Q_d^{thres}	Required Q threshold for demand d.
$A(d,r)$, $B(d,r)$	Linear impairments and constants associated to the route r of the demand d.
ξ_{energy}	Weight of energy in the objective function.
ξ_Q	Weight of number of demands below the Q threshold in the objective function.
ε^t, ε^r	Power consumption per wavelength for a transponder and receiver in a node.
ε^s	Power consumption per wavelength due to the switching devices at a node such as a MEMS optical switch.
ε^a,Φ_n	Power consumption of an in-line amplifier and electronic control power consumption of an optical cross connect.
a_e	Total power consumption of in-line amplifiers on link e.
z_{ei}	Equal to 1 if node i is a member of link e.

The following notation is used for the variables:

x_{drw}	Binary, equal to 1 if the demand d is routed using route r and wavelength w.
δ_{ew}	Binary, equal to 1 if the wavelength channel w is used on the link e.
s_d	Real positive, the statistical XPM variance assigned to demand d.
q_d	Binary, equal to 1 if the Q of the demand d is lower than the threshold.
l_e ,n_i	Binary, equal to 1 if link e and node i are activated, respectively.

Finally, the MILP formulation is as follows:

$$\min \xi_{energy} \cdot energy + \xi_Q \cdot \sum_{d\in D} q_d \tag{7}$$

subject to

$$\sum_{r\in R(d)} \sum_{w\in W} x_{drw} = 1, \quad \forall d \in D \tag{8}$$

$$\sum_{d\in D} \sum_{r\in R(d)} t_{dre} \cdot x_{drw} = y_{ew}, \quad \forall e \in E, w \in W \tag{9}$$

$$\sum_{e\in E} t_{dre} \cdot \sum_{\substack{w'=w-\eta \\ w'\neq w}}^{w+\eta} y_{ew'} \cdot s^2_{XPM}(e,w,w') - (1 - x_{drw}) \le s_d, \quad \forall d \in D, r \in R(d), w \in W \tag{10}$$

$$s_d \le \sum_{r\in R(d)} \sum_{w\in W} x_{drw} \cdot \left[\left(\frac{A(d,r)}{Q_d^{thres}} \right)^2 - B(d,r) \right] + q_d, \quad \forall d \in D \tag{11}$$

$$\sum_{r\in R(d)} \sum_{w\in W} x_{drw} \cdot \left[\left(\frac{A(d,r)}{Q_d^{thres}} \right)^2 - B(d,r) \right] - s_d + q_d \le 1, \quad \forall d \in D \tag{12}$$

$$M.l_e \ge \delta_{ew}, \ldots w \in W, e \in E \tag{13}$$

$$M.n_i \ge z_{ie}\delta_{ew}, \ldots w \in W, e \in E \tag{14}$$

$$energy = \sum_{e\in E} a_e l_e + \sum_{i\in N} \phi_i n_i + \sum_{e\in E} \varepsilon^s \sum_{w\in W} \delta_{ew} \tag{15}$$

The objective function (7) minimizes both energy and number of lightpaths above the BER threshold. Constraint (8) guarantees that each lightpath request is assigned only one route and wavelength, whereas constraint (9) makes sure that there is no wavelength conflict on different lightpaths passing through the same link. Constraint (10) computes the XPM noise of each demand according to its route and the occupation of the network using the restricted linear model for $s^2_{XPM}(e,\lambda,i)$ detailed in [12]. The XPM noise is compared to the signal quality threshold of the used route in constraints (11) and (12) in order to identify the demands having an associated *Q-factor* higher than the *Q-threshold* in constraint (11) and smaller than the *Q-threshold* in constraint (12). Constraints (13) and (14) define the value of the decision variables according to whether a link or a node is in use, i.e., activated, or not. Finally constraint (15) calculates the energy consumption of the network to be minimized in the ILP model. The first term in constraint (15) corresponds to the power consumption of the optical amplifiers in the network, while the second term is the idle power consumption of the optical cross connects, which is the power drained by the electronic control unit when the node is active. Finally the third term corresponds to the power consumption of the optical MEMS switches. Note that in order to calculate the total power consumption of the optical WDM layer, the transponder power consumption also need to be taken into account.

After solving the MILP, the following formula is used to compute the total power *consumption:*

$$POW = \sum_{e\in E} a_e l_e + \sum_{i\in N} \phi_i n_i + \sum_{e\in E} \varepsilon^s \sum_{w\in W} \delta_{ew} - 2\varepsilon^s |D| + (\varepsilon^t + \varepsilon^r)|D| \tag{16}$$

The first three terms in eq. (16) are the same as in constraint (15) since they are dependent on the variables in the MILP model. In order to derive the actual power consumption we need to subtract from the third term, the optical switching power for source and destination nodes of the lightpath requests which was kept for simplicity in constraint (15) since the constant values will not change the solution of MILP. The last term in eq. (16) accounts for power consumption of transponders.

IV. IA-RWA AND EA-RWA

In order to evaluate the performance of our IEA-RWA approach, two RWA schemes are presented for benchmarking: (1) impairment-aware RWA (IA-RWA), where the number of connections over the BER threshold is minimized; (2) energy-aware RWA (EA-RWA) where power consumption in the optical layer is minimized while solving the conventional static RWA problem. The ILP formulation for each one of the benchmarking strategy is presented next.

A. *IA-RWA ILP formulation*

$$\min \sum_{d\in D} q_d \tag{17}$$

Subject to the same constraints of the ILP presented in section III since constraints (13)-(15) are needed for the calculation of the power consumption.

B. *EA-RWA ILP formulation*

$$\min \varepsilon_{energy} \cdot energy \tag{18}$$

Subject to the same constraints of the ILP presented in section III except for (10)-(12). EA-RWA minimizes the power consumption regardless of the BER-threshold value. In order to reduce the computational time of the ILP, after solving the model once, the impairment values for each BER-threshold are computed separately by using the same formulations defined in (10)-(12).

V. ILLUSTRATIVE NUMERICAL RESULTS

The trade-off between power consumption and optical signal quality is analyzed by comparing the EA-RWA, IA-RWA and our multi-objective IEA-RWA approaches under different network loads and BER thresholds (BER-ths). Results are obtained by running an ILP solver [20] on a 16-node and 23-link optical topology [17], with link distances ranging from 218 to 783 km, where each fiber link is supporting 16 wavelengths. Different sets of connection requests, i.e., lightpaths with capacity of 40Gbps are generated among source and destination nodes according to a uniform distribution. For each node pair a set of *k*=3 shortest paths is pre-computed. The power consumption parameters are set according to [21] as follows: (1) electronic control power consumption at each node is Φ_n=150W; (2) transponder's power consumption $\varepsilon^t + \varepsilon^r$=5.9W; (3) 3D MEMS switching power consumption ε^s=0.107W per wavelength; (4) power consumed by in-line amplifiers is computed as $a_e = \varepsilon^a \cdot A_e$ where ε^a = 9W and $A_e = \lfloor (d_e/80\text{km}) + 2 \rfloor$.

After performing a set of experiments we obtained ξ_Q=1 and

ξ_{energy}=0.01. Note that these values balance the trade-off between power consumption and signal quality. Each set of results are generated for three different BER-ths: 1E-9, 1E-11, and 1E-13 ($Q^{thres} \approx$ 6, 6.7, and 7.3, respectively) and the number of connections which stay above the threshold value is measured.

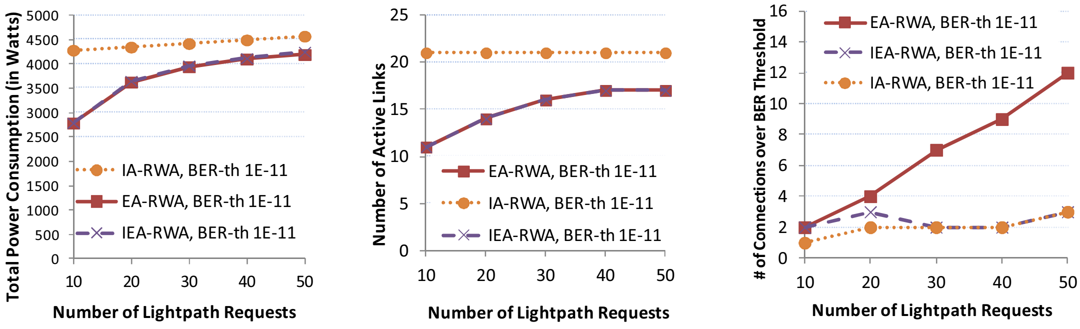
A. IEA-RWA performance evaluation

The performance of IEA-RWA, compared to IA-RWA and EA-RWA approaches, is evaluated in Fig. 1 in terms of three different metrics (i.e., power consumption, number of active links, and connections over the BER-th) by setting the BER-th equal to 1E-11. Fig. 1(a) plots the network power consumption against the number of lightpath requests. Interestingly, both EA-RWA and IEA-RWA approaches achieve the same reduction in total power consumption (ranging from 7% up to 35%) compared to the IA-RWA approach. As shown in Fig. 1(b), the proposed EIA-RWA uses the same number of fiber links as EA-RWA. In contrast, IA-RWA activates every fiber link in the network, to minimize the number of requests above the BER-threshold. This is because IA-RWA tends to choose short routes to minimize the effect of ASE noise, and it encourages the assignment of wavelengths that are spread around in the optical spectrum to avoid non-linear impairments and cross-talk.

Additionally, Fig. 1(c) shows how combining both energy and impairments objectives in a single optimization model (i.e., IEA-RWA) provides signal quality levels that are very close to the ones provided by the IA-RWA approach while minimizing power consumption. On the other hand, relatively poor performance in terms of optical signal quality is obtained using EA-RWA. The number of connections where BER is over the threshold reaches up to 24% of the requests in EA-RWA in contrast to only 4% using our IEA-RWA approach, which closely follows the results obtained using the IA-RWA scheme.

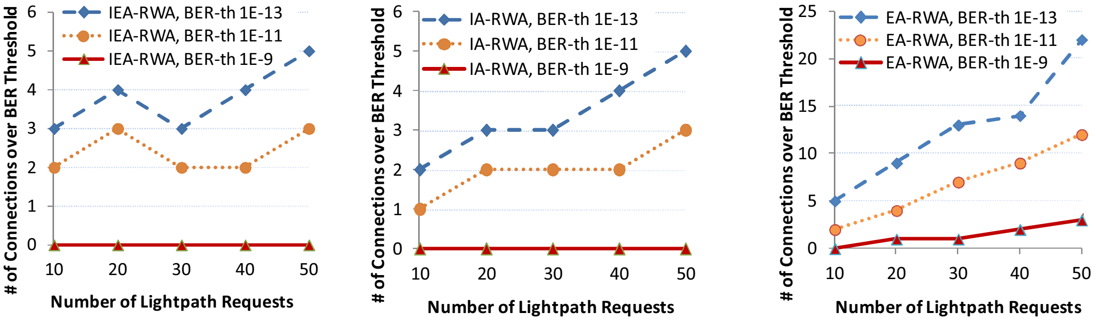
B. Impact of BER-th on the performance of different RWA approaches

Aiming at better analyzing the performance of our approach in terms of signal quality, three different BER-ths are considered: 1E-9, 1E-11, and 1E-13. Fig. 2 shows the number of lightpaths ensuring the above-mentioned thresholds using each of the RWA approaches. When the BER-th is relaxed, i.e., 1E-9, every connection request can be satisfied in terms of signal quality using both IA-RWA (Fig. 2(a)) and IEA-RWA (Fig. 2(b)). This is not the case when the EA-RWA is used, where a non-negligible number of connections are served with lower quality than the one required, as shown in Fig. 2(c). As soon as more stringent BER-th values are chosen, the number of lightpaths whose signal quality is worse than the threshold increases in all three approaches. Notwithstanding, it is worth noting how that number goes up to 46 % of the total lightpath requests using the EA-RWA when the most stringent BER threshold, 1E-13, is required.



(a) (b) (c)

Fig. 1. Comparison of three RWA approaches in terms of (a) total network power consumption, (b) number of active fiber links, and (c) number of lightpath requests over BER threshold vs. number of lightpath requests. (BER threshold is set to 1E-11 for all approaches.)



(a) (b) (c)

Fig. 2. Comparison of the impact of three different BER threshold values in (a) IEA-RWA, (b) IA-RWA, and (c) EA-RWA in terms of number of lightpath requests over BER threshold vs. number of lightpath requests.

Our combined IEA-RWA approach performs almost identically to the IA-RWA in terms of number of connections over any BER-th, even for the most stringent one.

VI. CONCLUSIONS

In this study we addressed the tradeoff between minimization of energy consumption and signal quality optimization in transparent WDM networks. We proposed a combined impairment and energy-aware RWA (IEA-RWA) approach that incorporates both linear and non-linear physical impairments into the energy-aware RWA problem.

We compared the performance of the proposed IEA-RWA with the conventional IA-RWA and EA-RWA approaches. It was confirmed that minimizing energy may result in a drastic signal degradation (signal quality below the required level was observed in up to 50 % of the computed lightpaths). This is a consequence of the fact that trying to lower the number of active network resources (i.e., to put them into sleep mode) increases the load on some specific links. On the other hand, focusing only on the optimization of the signal quality (IA-RWA) may result in the wasting of a large amount of energy, i.e., spreading the traffic in order to minimize the maximum load of the links, increase the number of active resources in the network.

With this tradeoff in mind our IEA-RWA approach proved to be able to significantly reduce power consumption (almost reaching the optimum level given by an EA-RWA approach) while guaranteeing the required signal quality (almost reaching IA-RWA levels).

REFERENCES

[1] Y. Zhang, P. Chowdhury, M. Tornatore, and B. Mukherjee, “Energy efficiency in telecom optical networks,” IEEE Communications Surveys & Tutorials, vol. 12, no. 4, 2010.

[2] A. Tzanakaki, K. Katrinis, T. Politi, A. Stavdas, M. Pikavet, P. V. Daele, D. Simeonidou, M. J. O. Mahony, S. Aleksic, L. Wosinska, and P. Monti, “Dimensioning the future pan-european optical network with energy efficiency considerations,” IEEE/OSA Journal of Optical Communication and Networking, vol. 3, no. 4, 2011.

[3] A. Ahmad, A. Bianco, E. Bonetto, D. Cuda, G. G. Castillo, and F. Neri, “Power-aware logical topology design heuristics in wavelength-routing networks,” in Proc. ONDM, February 2011.

[4] Y.Wu, L. Chiaraviglio, M. Mellia, and F. Neri, “Power aware routing and wavelength assignment in optical networks,” in Proc. ECOC, September 2009.

[5] P. Wiatr, P. Monti, and L. Wosinska, “Power savings versus network performance in dynamically provisioned WDM networks” IEEE Communication Magazine - Optical Communication Series, accepted, 2011.

[6] C. Cavdar, “Energy-efficient connection provisioning in WDM optical networks,” in Proc. OFC, March 2011.

[7] A. Muhammad, P. Monti, I. Cerutti, L. Wosinska, P. Castoldi, and A. Tzanakaki, “Energy-efficient wdm network planning with dedicated protection resources in sleep mode,” in Proc. Globecom, December 2010.

[8] L. Wosinska, C. Cavdar, and F. Buzluca, “Energy-efficient design of survivable wdm networks with shared backup,” in Proc. Globecom, December 2010.

[9] A. Jirattigalachote, C. Cavdar, P. Monti, L. Wosinska, and A. Tzanakaki, “Energy efficiency in telecom optical networks,” Optical Switching and Networking (OSN) Journal, special issue on Green Communication and Networking, vol. 8, no. 3, pp. 201–213, July 2011.

[10] S. Azodolmolky, M. Klinkowskiv, E. Marin, D. Careglio, J. S. Pareta, and J. Tomkos, “A survey on physical layer impairments aware routing and wavelength assignment algorithms in optical networks,” Computer Networks Journal, vol. 7, no. 53, pp. 926–944, May 2009.

[11] C. Bastos-Filho, D. Araujo, E. Barboza, D. Chaves, and J. Martins-Filh, “Design of transparent optical networks considering physical impairments, capex and energy consumption,” in Proc. ICTON, June 2011.

[12] M. Ruiz, L. Velasco, P. Monti, and L. Wosinska, “Fast and accurate statistical q-factor computation for impairment-aware rwa problems,” Universitat Politecnica de Catalunya (UPC), Barcellona, Spain, Tech. Rep. UPC-DAC-RR-CBA-2011-7, September 2011.

[13] Traffic measurements and models in multi-service networks project, Celtic project, “TRAMMS IP Traffic report no. 1, April 2008”, http://projects.celticinitiative.org/tramms/.

[14] Traffic measurements and models in multi-service networks project, Celtic project, “TRAMMS IP Traffic report no. 3, June 2008”, http://projects.celticinitiative.org/tramms/.

[15] A. Jirattigalachote, P. Monti, L. Wosinska, K. Katrinis, A. Tzanakaki, “ICBR-diff: an impairment constraint based routing strategy with quality of signal differentiation,” Academy Publisher J. of Netw., vol. 5, pp. 1279-1289, 2010.

[16] M. Pióro and D. Medhi, *Routing, Flow, and Capacity Design in Communication and Computer Networks*, Elsevier, 2004.

[17] S. De Maesschalck, D. Colle, I. Lievens, M. Pickavet, and P. Demeester, “Pan-european optical transport networks: an availability-based comparison,” Photonic Network Communications, vol. 5, no. 20, pp. 203-225, 2003.

[18] A. Cartaxo, “Cross-phase modulation in intensity modulation-direct detection wdm systems with multiple optical amplifiers and dispersion compensators,” IEEE/OSA Journal of Lightwave Technology, vol.17, pp.178-190, 1999.

[19] S. Pachnicke and E. Voges, "Analytical assessment of the Q-factor due to cross-phase modulation (XPM) in multispan WDM transmission systems," in Proc. SPIE, 2003.

[20] IBM ILOG Optimization Products, Licence provided by Academic Initiative, https://www-304.ibm.com/support/docview. wss? uid=swg214 1 9058.

[21] S. Aleksic, “Analysis of power consumption in future high-capacity network nodes,” J. Opt. Commun.Netw., no. 3, pp. 245–258, vol. 1, 2009.