Minimizing Power Consumption in Mixed Line-Rate Translucent Optical Networks

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Abstract— **This work proposes a Routing and Wavelength Assignment (RWA) algorithm for network planning aiming to minimize the power expended in Mixed Line-Rate (MLR) translucent optical networks by reducing the number of power consuming components such as regenerators and add/drop terminals, using several data rates and modulation formats. In particular, an algorithm for solving the Energy-Aware RWA (EA-RWA) problem in MLR translucent networks based on an Integer Linear Programming (ILP) formulation is proposed. Our study shows that energy savings can be obtained by minimizing the power consumed at the optical layer, through the reduction of the number of power-consuming components in conjunction with the data rate and modulation format adaptation.**

Keywords- ***Network planning, Energy-aware Routing and Wavelength Assignment, Energy efficiency.***

I. Introduction

Optical networks using Wavelength Division Multiplexing (WDM) technology modulate multiple channels over a single fiber. The most common architecture utilized for establishing communication in WDM optical networks is wavelength routing, where the communication between a source and a destination node is performed by setting up optical channels between them, called lightpaths [1]. The problem of selecting appropriate paths and wavelengths for a set of requested connections is called Routing and Wavelength Assignment (RWA). Optical networks belong to one of three categories: all-optical *transparent* networks, where data signals remain in the optical domain for the entire path, *translucent* networks, where signal regeneration is only possible at some intermediate nodes, or *opaque* networks where the signal undergoes Optical-Electrical-Optical (OEO) conversion at every network node. The focus in this paper is on translucent networks that can provide all-optical end-to-end connections but they can also regenerate the signal if needed.

The transport capabilities of core networks are continuously upgraded, in order to meet the increasing traffic demand. While the industry wants to move quickly to higher capacity optical transport networks and enhance the 10-Gbps systems currently deployed, there are a number of technology issues that need to be addressed. As the optical technology for higher data rates matures and becomes more efficient, 40, and 100 Gbps rate connections will be incorporated in existing 10 Gbps network systems [2]. Thus, a transport network will end up managing a variety of line rates, what is usually referred to as a mixed line rate (MLR) system. Planning a MLR network to support several data rates over the same system, can reduce the total cost of the transponders by exploiting the heterogeneity and flexibility that is provided by MLR transmissions.

Another important issue in optical networks is the minimization of power consumption. The continuing deployment and upgrade of optical telecommunication networks drive up power consumption, in a way that makes operators worry that future power consumption levels may pose constraints on the growth of telecommunications infrastructures. Even though Information and Communication Technologies (ICT) are already bringing massive environmental benefits (e.g., through the use of telecommuting, video conferencing, electronic news, etc), the need for ICT to keep its own power consumption growth under control is also becoming evident [3]. It seems that an energy-aware approach is increasingly needed during the design, implementation, and operation of optical networks, which carry more than 80 percent of the world's long-distance traffic. Two different approaches can be explored to reduce power consumption in optical networks: the improvement of the energy efficiency of the equipment and the energy awareness of the algorithms used.

A thorough study on the power consumption of optical and electronic switching systems was published in [3] and [4]. Most of the current research work tries to minimize power consumption in optical networks utilizing techniques such as traffic grooming [5] and energy-efficient routing (e.g., setting some of the networks' components in sleep mode [6]). Additionally, the power consumption has been evaluated and compared for different fixed and flexible network architectures [7]. Results show that in order to optimize the total power consumption and footprint of the network, the architecture of each node has to be selected according to the amount and pattern of the add/drop and regenerated traffic and the number of pairs of fibers convergent to the node. Power-aware MLR in IP over WDM networks is examined in [8].

In [8] the WDM core network was analyzed for mixed-line rate and reach/bandwidth adaptive scenarios; the latter was realized by optical orthogonal frequency division multiplexing (O-OFDM). The comparison between MLR and bandwidth/reach adaptive is mainly done in the WDM layer as the IP layer showed no significant differences between adaptive and MLR networks in regards to power consumption for different topologies and network scenarios. Although the adaptive scenario shows to be more hardware efficient in terms of total number of transponders, the mixed-line rate approach has slight advantages regarding cost and power.

In [9], authors examine how the de-facto standard for long-haul 100 Gbps communication (polarization-division-multiplexed quaternary phase-shift keying (PDM-QPSK) with coherent detection and DSP) can be upgraded to an elastic scheme. They investigate two possible schemes for elasticity: 1) modulation-format adaptation and 2) symbol-rate adaptation, in each case assessing the power consumption of the transceiver and the reach of optical signals as a function of the data rate, both factors having a major impact on the overall power consumption of the network. Performance results with respect to static networks for the case of a European backbone network showed potential for up to 30% of energy savings when the two schemes are combined.

Our previous work [10] focused on single line rate networks (SLR) with the objective to plan optical WDM networks so as to minimize the energy expended, by reducing the number of energy-consuming components, such as amplifiers, regenerators, add/drop terminals, optical fibers, etc.

This work deals with power minimization in optical networks using an Integer Linear Programming (ILP) formulation by incorporating constraints for translucent MLR networks (that includes regenerators), power consumption issues, as well as data rate and modulation format adaptation. The models from work in [9] are incorporated to our formulation in order to find the optimal combination of data rates and modulation formats and reduce the power consumption of the network. In addition, a scalable node architecture with reconfigurable optical add/drop multiplexer (ROADM) was chosen in order to support the dynamic traffic evolution of the networks [7] and minimize the power consumption of specific parts of the node architecture. Our results show that energy savings are achieved compared to SLR networks.

The rest of the paper is organized as follows. In Section II the network architecture model is introduced and the relationship between power consumption and lightpath establishment is examined. The power-aware MLR RWA algorithm is described in Section III. Performance simulation results are presented in Section IV, while our conclusions follow in Section V.

II. Network Model And Power Consumption

An optical backbone network consists of the interconnection of optical cross-connect switches (OXC) by pairs of bidirectional fiber links. In a WDM optical system a receiver-transmitter pair, known as transponder (TSP) is required in order to receive/transmit data via optical channels. Data rate-adaptive TSPs can be used to follow the pronounced variations in requested bandwidth in core networks and therefore allow significant energy savings compared to static networks configured to support the peak traffic at all times. Modulation-format and data-rate adaptation have a major impact on power consumption and the transmission reach of optical signals [9]. Transmission reach is defined as the distance an optical signal can travel before its quality and bit-error-ratio (BER) degrade to an unacceptable level. Many factors affect the transmission reach: the launched power of the signal, the modulation format, the bit rate, the type of amplification, the dispersion map, the interference from other signals, etc.

A MLR network manages a variety of line rates and modulation formats. In Fig. 1, for example, a network is represented that supports several line rates (R={25,50,100} Gbps) over a single fiber. Each link consists of a single fiber and a single fiber can have a combination of line rates and modulation formats, each on a separate wavelength. Thus, the routing and wavelength-assignment (RWA) problem is modified to the routing, wavelength, rate, and modulation assignment problem. Typically, for a given modulation format, higher line-rate transmissions have a shorter reach than lower line-rate transmissions. Also, different modulation formats have different transmission reach for a given line rate. The combination of different line rates and modulation formats leads to different transmission reach and also leads to different levels of power consumption for the network.

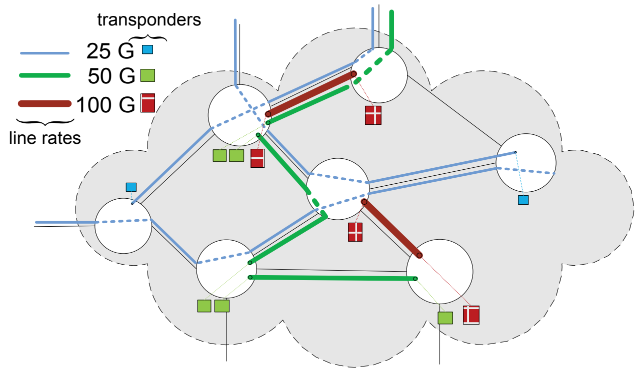

Fig. 1. A network that supports mixed line rates (MLR).

In large networks involving long geographical distances the only satisfactory method to overcome the physical impairments and to keep the Quality of Transmission (QoT) above a given threshold, is signal regeneration. Since regeneration consumes substantial energy, reducing the number of regenerators used is important for minimizing the overall power consumption.

The node architecture (OXC) considered in this work is illustrated in Fig. 2. The OXC architecture can remotely configure all transit traffic with a broadcast and select architecture. The incoming channels (for example from box A in Fig. 2) are broadcasted (with a splitter) to all other network interfaces (for example boxes B and C in Fig. 2), as shown from the lines in the center of Fig. 2.

This OXC architecture offers full flexibility of add/drop ports, meaning that traffic can be added/dropped to/from an arbitrary transmission fiber originating from or terminating at the node (directionless feature) and in any wavelength (colorless feature). As each add/drop terminal allows a wavelength to be added/dropped only once, the architecture uses additional terminals to allow adding/dropping a specific wavelength more than once (contentionless feature). The constraint of this configuration is that only one unique wavelength can be dropped at an add/drop terminal, because a Wavelength Selective Switch (WSS) can only drop the same wavelength once to its output port. This architecture was chosen because of its inherent ability to support dynamic traffic evolution in a flexible and economic manner and is probably the most cost-efficient architecture from the operator's perspective, since components can be added on a node that needs to be upgraded, without affecting existing transit traffic, thus offering a "pay-as-you-grow" property.

A power consuming device of the OXC is the add/drop terminal which is mainly implemented by WSSs and amplifiers. One way to reduce the number of add/drop terminals, is to avoid dropping the same wavelength many times at one node. To describe the technique utilized for reducing the number of add/drop terminals used during the lightpath establishment of the requested connections, a short example is given in Figs. 3a and 3b. In this example, there exists one established lightpath from A to B and one from C to B. In Fig. 3a the two lightpaths use wavelength w_1. This means that wavelength w_1 is dropped at node B twice. Using the architecture of Fig. 2, two add/drop terminals are needed in node B for this lightpath establishment. On the other hand, in Fig. 3b, the two lightpaths are established using different wavelengths and as a consequence only one add/drop terminal is needed in node B to drop these wavelengths. Thus, the second terminal of node B can be turned off, leading to lower levels of power consumption.

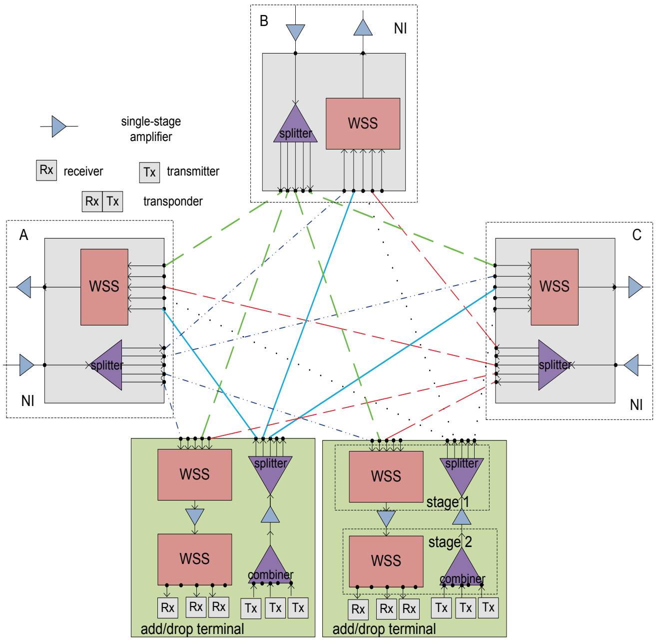

Fig. 2. Colorless, directionless, contentionless OXC

Power is consumed in a WDM network when lightpaths are activated over the links and nodes of the network. Different solutions of the RWA problem result in different needs in terms of network equipment (e.g., transponders, regenerators) required for setting up the lightpaths, and consequently different energy and operational costs.

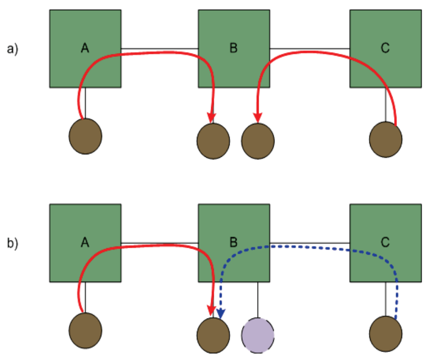

Fig. 3. Power saving by powering off add/drop terminals.

III. Energy-aware RWA Algorithm

The energy-aware RWA algorithm for MLR networks proposed in this work (denoted as EA-MLR) is given a network $G=(V,E)$, where V denotes the set of nodes and E denotes the set of (point-to-point) fiber-links. Each fiber-link is able to support a set $C=\{1,2,...,W\}$ of W distinct wavelengths, a set $R=\{r_1,r_2,\ldots,r_G\}$ of G different data rates, and a set $M=\{m_1,m_2,\ldots,m_I\}$ of I modulation formats. An a-priori known (static) traffic scenario is given in the form of a matrix of aggregated demands Λ in Gbps, called the traffic matrix. Then, Λ_{sd} denotes the requested bandwidth from source s to destination d, that is Λ_{sd} is the end-to-end demand of commodity (s,d). Each transponder is able to adapt its transmission rate and modulation format. The transmission reach for every data rate and every modulation format is different and equal to D_m^r, where m is the modulation format and r is the data rate. Moreover, every combination of data rate and modulation format leads to different power consumption for the transponder.

The algorithm considers the planning of *translucent* MLR networks in which signal regeneration may be performed at intermediated nodes of an end-to-end connection. In such a network, some connections need regeneration at some intermediate nodes in order for their QoT to remain above a desired threshold. For simplicity, a regenerator is assumed to be implemented by a transponder (transmitter-receiver connected back-to-back) and thus its power consumption is the same as the power consumption of a transponder with the same rate and modulation format. In Fig. 2, a single transponder is shown as two different devices (a transmitter and a receiver). When a lightpath is regenerated, it can also change its wavelength. Thus, a regenerator functions also as a wavelength converter. To achieve this, tunable transmitters are necessary in order to support wavelength conversion.

The algorithm's objective is to minimize the total power consumed by active devices (e.g., add/drop terminals, regenerators, transponders) in MLR *translucent* optical networks and also to use the appropriate combination of transponders that differ in data rate and modulation format in order to satisfy all the requested demands while also satisfying the transmission reach constraints. The problem is solved based on an integer linear programming (ILP) formulation.

A. ILP algorithm

The algorithm pre-calculates a set P_{ij} of k candidate paths between all pairs of nodes i and j and this set represents the solution space of the algorithm. Every path is characterized as transparent if its length is lower than the transmission reach D_m^r, and as non-transparent if its length is larger than that. The values of the transmission reach are based on [9] and specific values are reported in Section IV. Besides the traditional constraints of a RWA algorithm, the proposed ILP formulation has additional constraints to satisfy the maximum transmission reach of every data rate and modulation format and also minimizes the number of add/drop terminals (shown in the example of Fig. 3).

The following notation is used in order to formulate the problem.

Parameters:

- $s,d \in V$**:** source and destination network nodes
- $l \in L$**:** network links
- $w \in C$**:** an available wavelength
- $p \in P_{ij}$**:** a candidate path from node i to node j
- $r \in R$: a transmission line rate
- $m \in M$: a modulation format

Constants:

- Λ_{sd}: the number of requested connections from s to d
- $P_{A/D}$: power consumption of an add/drop terminal
- P_m^r: power consumption of a transponder/regenerator at rate r and modulation format m.

Variables:

- $x_{pw}^{r,m}$: a Boolean variable equal to 1 if lightpath (*p*,*w*,*r*,*m*), that is, wavelength *w* with rate *r* and modulation format *m* over path $p \in P_{ij}$, is utilized to connect (*i*,*j*), and equal to 0, otherwise.
- $f_{sd,ij}^{r,m}$: an integer variable that declares the number of lightpaths of rate *r* and modulation format *m* between nodes *i* and *j* that are used to serve commodity (*s*,*d*).

Note that in this formulation, Boolean variable $x_{pw}^{r,m}$ may correspond to a lightpath (*p*,*w*,*r*,*m*) that serves *transparently* an end-to-end demand between the given source and destination pair (*s*,*d*), or to an intermediate lightpath of a *translucent* connection that is realized by a series of lightpaths. In the latter case, the start and/or the end of the lightpath (*p*,*w*,*r*,*m*) are intermediate regeneration node(s) for the translucent connection. Variables $f_{sd,ij}^{r,m}$ are used as flow variables that identify the lightpaths used to serve the traffic of commodity (*s*,*d*). The lightpaths identified by the $f_{sd,ij}^{r,m}$ variables are realized though specific paths and wavelengths by the corresponding $x_{pw}^{r,m}$ variables.

- y_n : an integer that denotes the total number of add/drop terminals required at node *n*.

Objective

Minimize: $$P_{A/D} \cdot \sum_n y_n + \sum_p \sum_w \sum_r \sum_m P_m^r \cdot x_{pw}^{r,m} \quad (1)$$

subject to the following constraints:

- Capacity constraints at source node:

$$\sum_r \sum_m \sum_j r \cdot f_{sd,sj}^{r,m} \geq \Lambda_{sd}, \text{ for all } sd \text{ pairs} \quad (2)$$

- Capacity constraints at destination node:

$$\sum_r \sum_m \sum_i r \cdot f_{sd,id}^{r,m} \geq \Lambda_{sd}, \text{ for all } sd \text{ pairs} \quad (3)$$

- Flow conservation constraint (regenerator allocation):

$$\sum_i f_{sd,in}^{r,m} = \sum_j f_{sd,nj}^{r,m}, \text{ for all } sd \text{ pairs, for all } n \in V, \text{ all } r \in \mathrm{R} \text{ and } m \in M \quad (4)$$

- Lightpath assignment constraint:

$$\sum_s \sum_d f_{sd,ij}^{r,m} = \sum_{p \in P_{ij}} \sum_w x_{pw}^{r,m}, \text{ for all } i,j \in V, \text{ for all } r \in \mathrm{R} \text{ and for all } m \in M \quad (5)$$

- Distinct wavelength assignment constraint:

$$\sum_{p:l \in p} \sum_r \sum_m x_{pw}^{r,m} \leq 1 \text{ for all } l \in L, \text{ for all } w \in C \quad (6)$$

- Transmission reach constraint:

$$\sum_{l \in p} D_l \cdot x_{pw}^{r,m} < D_m^r \text{ for all } p \in P, \text{ for all } w \in C, \text{ for all } r \in \mathrm{R} \text{ and for all } m \in M \quad (7)$$

- Number of add terminals per node:

$$\sum_{p \in P|n=s} \sum_r \sum_m x_{pw}^{r,m} \leq y_n \text{ for all } w \in C, \text{ for all } n \in V \quad (8)$$

- Number of drop terminals per node:

$$\sum_{p \in P|n=d} \sum_r \sum_m x_{pw}^{r,m} \leq y_n \text{ for all } w \in C, \text{ for all } n \in V \quad (9)$$

The objective function is chosen to minimize the total power consumed by the add/drop terminals, and the adaptive rate-format transponders/regenerators that are used to establish a set of requested connections. Constraints (2)-(4) correspond to the lightpath routing constraints, where each connection (*s*,*d*) should have node *s* as starting node and node *d* as the ending node, while any intermediate node can be used as a regenerator. Constraint (2) ensures that the lightpaths that start from the source node of an end-to-end demand have total capacity higher than the requested demand. Constraint (3) functions in a similar way at the destination node, while constraint (4) ensures the flow conservation of lightpaths at intermediate regeneration nodes. Constraint (5) assigns paths and wavelengths to the required lightpaths between all node pairs of the network. Constraint (5) assigns paths and wavelengths to the required lightpaths between all node pairs of the network. Constraint (6) ensures that each wavelength is used at most once on each fiber. Constraint (7) prohibits the utilization of lightpaths over paths that exceed the maximum transmission reach for each data rate and modulation format. Constraints (8)-(9) count the number of add/drop terminals. The wavelength continuity constraint is implicitly taken into account by the definition of the $x_{pw}^{r,m}$ variable.

TABLE I. NUMBER OF VARIABLES AND CONSTRAINTS

Variables	***x*** $kN^2 \cdot W \cdot G \cdot I$	***f*** $N^4 \cdot G \cdot I$		***y*** N
Constraints	**(2)** N^2	**(3)** N^2	**(4)** $N^3 \cdot G \cdot I$	**(5)** $N^2 \cdot G \cdot I$
	(6) $L \cdot W$	**(7)** $kN^2 \cdot W \cdot G \cdot I$	**(8)** $N \cdot W$	**(9)** $N \cdot W$

Table I presents the number of variables and constraints required in the above ILP formulation. In this table $N = |V|$ denotes the number of nodes, $|E|=L$ the number of links, $|C|=W$ the number of wavelengths, $|R|=G$ the number of different rates, $|M|=I$ the number of different modulation formats, and *k* the number of pre-calculated shortest paths per connection.

IV. PERFORMANCE RESULTS

Simulation experiments were carried out to evaluate the performance of the proposed algorithm in a 6-node network (Fig. 4) with random traffic matrices and in the generic Deutsche Telekom (DT) network topology (Fig. 5) that comprises of 14 nodes and 26 links and starting with a realistic traffic matrix as identified in DICONET project [12], which is scaled up assuming a uniform increase of 34% per year to obtain matrices for years 2013 to 2021 (9 to 94 Tbps of traffic, respectively). The algorithms were implemented in Matlab and Gurobi [13] was used to solve the corresponding ILP problem. The link lengths are chosen so that some connections will require regeneration.

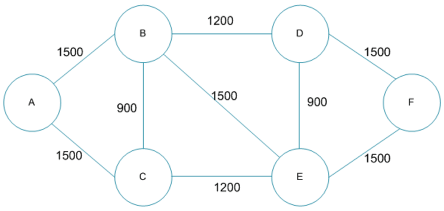

Fig. 4. Six-node network topology used in the simulation experiments

Fig. 5. DT network topology used in the simulation experiments

The characteristic transponder configurations are summarized in Table II (in compliance with the 50-GHz ITU-T frequency grid), where the format change does impact the reach but not the power consumption of the transponder while symbol-rate change impacts the power consumption but not the reach [9]. Moreover, the power consumption of an add/drop terminal is considered to be 110 W [14].

TABLE II
POWER CONSUMPTION FOR DIFFERENT TSP CONFIGURATIONS [9]

Data Rate (Gb/s)	Format	Reach (km)	Power Consumption (W)
25	PMD-QPSK	1200	189
	PMD-BPSK	2500	206
	SP-BPSK	3000	350
50	PMD-QPSK	1200	206
	PMD-BPSK	2500	350
75	PMD-QPSK	1200	255
	PS-QPSK	1800	350
100	PMD-QPSK	1200	350

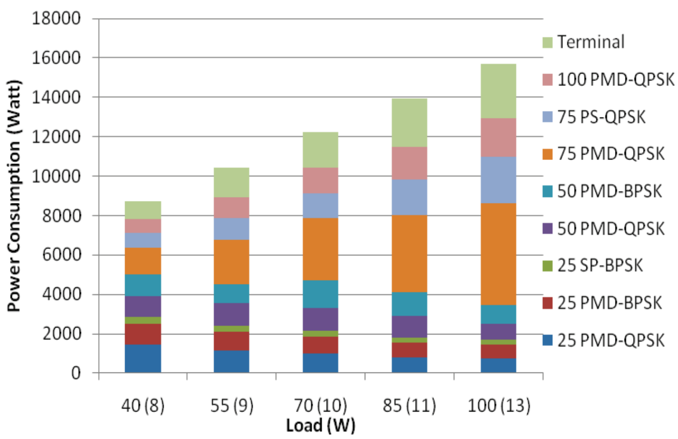

Fig 6. Power Consumption of the TSPs and add/drop terminals for the 6-node network versus the network load and the number of used wavelengths

For the 6-node network and for a given traffic load, 10 traffic matrices were randomly created, where the requested capacity for each (*s*,*d*) pair was an exponential random variable with average the given traffic load. In Fig. 6 the power consumption for the 6-node network for loads ranging from 40 to 100 Gbps, with a 15 Gbps step is depicted. The number of available wavelengths per link is shown in the brackets next to the traffic load. This number (available wavelength) corresponds to the minimum number of available wavelengths in order to achieve minimum power consumption. Lower number of available wavelengths lead to higher power consumption and higher number of available wavelengths have no impact on the power consumption. This fact can be seen in Table III where the power consumption for different number of wavelengths and loads equal to 70 and 100 Gbps is given. The power consumption includes only the power consumed by the TSPs (including regenerators) and the add/drop terminals. In Fig.6, the power consumption of the network is computed by the objective function of the EA-MLR algorithm presented in Section III. It is evident from Fig.6 that all the TSP configurations (line rates and modulation formats) are present in the network and are necessary to reduce the power consumption of the network. In a different case where some configurations (specific line rates and modulation formats) were not present in the solution then these configurations would not be necessary to minimize the power consumption, since the ILP algorithm produces the optimal solution. As can be seen also in Fig. 6, the number of high rate TSPs increases with the traffic load, while the number of lower rate TSPs decreases. Moreover, the add/drop terminals consume a measurable fraction of the power and should be taken into consideration during the minimization of the network power consumption.

In Fig. 7 the power consumption of the DT network for years 2013 to 2021 is depicted. The number of available wavelengths is chosen to be equal to 30, for simulation purposes. The figure illustrates the power consumption of the network when using the proposed EA-MLR algorithm and variations of the EA-MLR algorithm designed for SLR (25, 50, 75, and 100 Gbps) networks. The SLR algorithms are derived from the ILP formulation of Section III as a special case by assuming that there is only one available line rate and one modulation format. The modulation format of the SLR algorithms was chosen to be the standard PMD-QPSK. The transmission reach for this modulation format is given in Table II. The algorithms that use 25 and 50 Gbps are only able to produce solutions until the years 2017 and 2018 respectively. Also, a second mixed line rate algorithm (denoted as MLR) that minimizes the energy consumed by the TSPs but without minimizing the add/drop terminals is depicted. This minimization objective derives from the ILP of the Section III by eliminating the first term of objective function (1). It is clear from the figure that the EA-MLR algorithm leads to a network configuration that is the most efficient in terms of power consumption compared to the rest of the algorithms. The fact that the curves between EA-RWA and MLR are close is because the node degree of the DT network is small. Networks with larger node degrees would give higher differences between the two algorithms, but this comparison is left for future work.

TABLE III
POWER CONSUMPTION FOR DIFFERENT NUMBER OF WAVELENGTHS FOR THE 6-NODE NETWORK

Number of Wavelengths (W)	Power Consumption (W)	
	Load =70 Gbps	Load =100 Gbps
5	13466	18041
6	12648	16797
7	12354	16229
8	12255	15955
9	12240	15796
10	**12237**	15728
11	12237	15707
12	12237	15698
13	12237	**15695**
14	12237	15695

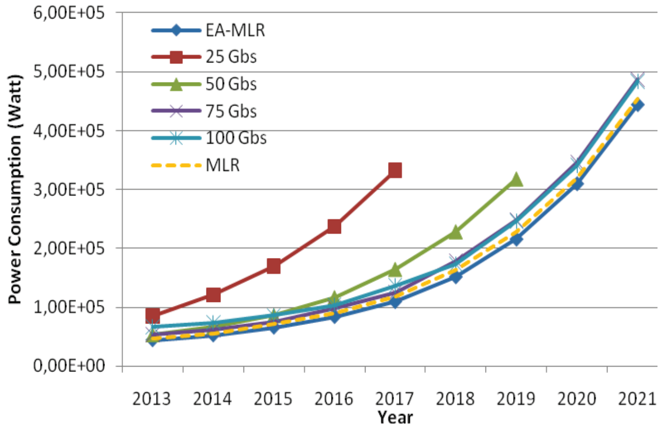

Fig 7. Power Consumption of the TSPs and add/drop terminals for the DT network

V. CONCLUSIONS

An EA-MLR RWA algorithm was presented that aims at minimizing the power consumed by the optical layer components when planning MLR translucent optical networks. The EA-MLR RWA algorithm considered takes into account the energy consumed by active devices all well as the adaptation of data rates and modulation formats. The algorithm considered was based on an ILP formulation, and our results obtained for small sized network and the DT network show that the proposed energy-aware MLR RWA algorithm performs significantly better in terms of power consumption than EA RWA algorithms designed for SLR networks, indicating that a significant decrease in the total power consumption can be achieved at the optical layer. Moreover, it is shown that the power consumption of the add/drop terminals should also be taken into account to further minimize the total power consumption of the network.

Future work focuses on the development of energy-efficient heuristic algorithms for MLR networks and also decomposition and relaxation techniques to solve the ILP problem. Subsequently, these algorithms will be compared to the corresponding ILP to investigate the optimality of the proposed methods. The comparison will be performed in networks with various node degrees.

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