Energy Efficient RWA Strategies for WDM Optical Networks

Konstantinos Manousakis, Archontoula Angeletou, and Emmanouel (Manos) Varvarigos

***Abstract*—We consider the energy minimization problem in optical networks from an algorithmic perspective. Our objective is 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. We initially present an algorithm for solving the energy-aware routing and wavelength assignment problem based on an integer linear programming formulation that incorporates energy consumption and physical impairments (through a maximum transmission reach parameter) into routing and wavelength assignment. We then present a second algorithm that decomposes the problem and uses a linear programming relaxation to address the problem in large scale networks. Simulations are performed to evaluate and compare the performance of the proposed algorithms. In previously published works, energy minimization derives mainly from the reduction of the electronic processing of the traffic and the bypass in the optical domain, while the energy consumed by the optical devices is usually neglected. We focus on the optical layer and show that energy reductions can be obtained in that layer also.**

***Index Terms*—Energy-aware routing and wavelength assignment; Energy-minimization; ILP formulation; Optical networks.**

I. INTRODUCTION

The continuing deployment and upgrade of optical telecommunication networks rapidly drive up power and energy consumption, in a way that makes operators worry that future energy consumption levels may pose constraints on communications growth that are more stringent than those posed by bandwidth limitations. As community concerns about environmental sustainability and green house effects grow, the power consumption of optical networks is also coming under closer scrutiny. The information technology infrastructure currently accounts for 1%–2% of global energy consumption, but this percentage is bound to rise, as more bandwidth-hungry applications (video streaming, high-definition television, cloud computing, etc.) continue to be deployed. In addition to the greenhouse footprint of communications, energy consumption also increases operational costs for the operators. Thus, it seems that an energy-aware approach is increasingly needed during the planning and operation of networks in general and optical networks in particular.

The most common architecture utilized for establishing communication in wavelength division multiplexing (WDM) optical networks is wavelength routing, where optical pulse trains are transmitted through lightpaths, that is, all-optical WDM channels that may span multiple consecutive fibers. WDM enables different connections to be established concurrently through a common set of fibers. The basic switching equipment in WDM optical networks is the optical cross-connect (OXC). The main components that give the desired dynamic characteristics in current OXC architectures are wavelength selective switches (WSSs).

Lightpaths are the basic switching entities for serving the connections in WDM optical networks, and their efficient establishment is an important issue, during both the planning and operation phases of a network. Given a set of connection requests (traffic matrix), the routing and wavelength assignment (RWA) problem consists of selecting a lightpath, that is, an appropriate path and a wavelength on the links of that path, for each requested connection. In general, the objective of the RWA problem is to maximize the traffic served for a given set of available resources, or equivalently to minimize the resources needed to establish the requested connections. In addition to serving the requested traffic, the quality of transmission (QoT) of the established lightpaths also has to remain above a desired threshold; algorithms that achieve this by appropriately placing regenerators and choosing the lightpaths to be used are often referred to as impairment-aware RWA algorithms.

Two different approaches can be explored to reduce energy consumption in optical networks: the improvement of the energy efficiency of the equipment and the energy awareness of the RWA algorithms. In this paper we follow the second approach, by proposing energy-aware routing and wavelength assignment (EA-RWA) algorithms to be used during network planning that aim at minimizing the energy consumption of the optical network. From an energy-consumption point of view, it is essential to make maximum use of the all-optical technology when establishing the requested connections and avoid, to the greatest degree possible, the electronic processing and the opto-electro-optical (OEO) conversion of the traffic at intermediate nodes. In the so-called *transparent* optical networks,

Manuscript received September 17, 2012; revised February 1, 2013; accepted February 10, 2013; published March 28, 2013 (Doc. ID 176418).

K. Manousakis is with the KIOS Research Center, Electrical and Computer Engineering Department, University of Cyprus, Cyprus (e-mail: manousakis.konstantinos@ucy.ac.cy).

A. Angeletou and E. Varvarigos (e-mail: manousak@ceid.upatras.gr) are with the Computer Engineering and Informatics Department, University of Patras, Patras, Greece.

Digitial Object Identifier 10.1364/JOCN.5.000338

1943-0620/13/040338-11$15.00/0

the signal remains always in the optical domain, avoiding OEO conversions. Continental networks may still require a small amount of regeneration in some nodes, making them *translucent*. In translucent networks, it is critical to minimize the number of required regenerators, since the energy consumed by electronic devices is much higher than that consumed by optical devices. In addition to deciding the placement of the regenerators, an EA-RWA algorithm also has to choose the lightpaths (i.e., paths and wavelengths) that will serve the traffic, so as to minimize the energy consumed by the modules they use.

We first give an integer linear programming (ILP) formulation for the EA-RWA problem that aims at minimizing the energy consumed by the various modules present in an optical network, such as the regenerators, amplifiers, wavelength selective switches, and fibers. We then decompose the EA-RWA problem for a general (translucent) network into 1) a regeneration placement problem and 2) an EA-RWA for transparent networks problem, where again ILP formulations are given to minimize energy consumption. The ILP of the decomposed problem is solved as a linear programming (LP) problem, by relaxing the integer constraints, in order to obtain solutions for large network topologies. In networks with multi-fiber optical links, the energy-aware algorithms tend to minimize the number of active fibers across the network. In addition to that (or in single-fiber networks), they also tend to minimize the number of active WSSs that are used at the network nodes. Our simulation results show that it is feasible to decrease by up to 65% the energy consumption in the optical layer in multi-fiber networks in realistic scenarios. Our algorithms assume that individual modules of a node (or link) can be switched off when not used by any lightpath. We also compare our algorithms to the case, already proposed in the literature, where only entire nodes and links (but not specific individual modules, as our approach assumes) can be switched off during the operation of a network. Our results show that if we are able to switch off specific components inside a node (and switch off an entire node when all the components inside it are switched off), we obtain better results than when we are only able to switch off entire nodes or links.

The rest of the paper is organized as follows. In Section II we present previous work on energy-aware planning of optical networks. In Section III we describe the network architecture model we use and explore the relationship between energy consumption and lightpath establishment. The EA-RWA algorithms are given in Section IV. Performance simulation results are presented in Section V, while our conclusions follow in Section VI.

II. Previous Work

The energy consumption of network devices in the Internet is examined in [1–4]. Recently, several approaches have been proposed for reducing the amount of network resources used in IP and WDM networks. These studies include grooming algorithms, optical bypass technologies, and techniques to switch off network elements [5–13]. Grooming algorithms try to aggregate and route low-rate demands over higher rate lightpaths so as to use a smaller number of network interfaces (NIs); optical bypassing tries to avoid OEO conversions, at least for large (elephant) flows; and switching off elements takes into account time variations in traffic, in order to reduce network over provisioning and the redundant devices used for fault recovery. All these algorithms try to route the traffic through a smaller number of network elements and can be combined with each other. A useful survey of energy-aware network design and networking equipment is presented in [14].

In [1] and [2], the authors discuss energy consumption at the IP layer. Specifically, the authors in [1] propose putting NIs and other router and switch components in sleep mode. Two such techniques are examined: uncoordinated sleeping, where each router or switch makes its own sleeping decision, and coordinated sleeping, where the routers collectively decide which interfaces to put to sleep. In [2] the authors propose an adaptive routing algorithm that reduces energy consumption by putting some equipment to sleep transiently within a specified period and then dynamically adjusting the routes.

The authors in [5] propose a traffic grooming mechanism for energy reduction by saving on the electrical ports of IP routers, using a mixed LP formulation. In [6], the authors examine the energy savings that can be achieved in IP-over-WDM networks through switching off router line cards during low-demand hours. In [7], the authors discuss energy and cost savings in multi-granular optical networks, considering the node model, the virtual topology design, and the uncertainty in the traffic matrix. They conclude that traffic grooming with optical bypass technology that binds low-rate IP data into a few high-speed lightpaths in order to reduce the number of electrical ports and the energy consumption of IP routers is a feasible and efficient solution.

Traffic grooming for energy reduction in WDM networks is also addressed in [8]. The authors show that by looking further into the modular physical architecture of a node during resource allocations, the number of active components, and hence the network energy consumption, can be significantly reduced through traffic grooming. Traffic grooming is also the subject of [9], where flow-based and interface-based formulations for green optical network design are provided. The former formulations capture to some extent the dynamic aspects of energy consumption by modeling equipment consumption as a linear function of the traffic load. The latter formulations capture the static aspect of equipment energy consumption, neglecting the impact of the traffic load. However, results are only provided for simple heuristic algorithms. Energy efficient traffic grooming in optical networks is also considered in [10], where an ILP formulation is given that aims at reducing the number of established lightpaths and the amount of electronically switched traffic. Results are given for small-sized networks.

In [11], the authors present an energy-efficient planning strategy for survivable WDM networks. They propose to put devices used for protection in sleep mode, assuming they can be promptly turned on upon a failure occurrence. They use an ILP formulation to properly select the lightpaths and show that power savings of up to 25% can be achieved in real case scenarios by putting in sleep mode link devices that support only protection lightpaths. They also showed that nodes' sleep modes can be exploited only under specific conditions, e.g., at low loads.

The authors in [12] consider turning off nodes and links under connectivity and maximum link utilization constraints, in order to minimize the energy these elements consume. They show that under these constraints, it is possible to power off some network elements and still guarantee full connectivity among sources and link utilization below a quality-of-service-induced threshold. They compared different heuristics and showed that during the night up to 50% of the nodes can be switched off, while during the day the percentage of nodes that can be turned off is negligible, since the whole network capacity is needed to satisfy the traffic demand. They noticed, however, that even during the day, it is possible to turn off some links. In [13] they extended their work by estimating the power consumption of nodes and links using realistic figures derived from available products and proposed an algorithm to select the nodes and links that could be turned off during off-peak hours. They estimated that it is possible to obtain energy savings of up to 23% in this way in an actual network.

In the present work we focus on the optical layer and a specific OXC node architecture, and we present algorithms for planning the network so as to minimize its energy consumption, switching off specific components inside the OXC as well as other modules in the network. The OXC architecture assumed is based on the current trend of optical networks that offer "pay as you grow" scalability. The modules to be switched off (equivalently, the ones to be used) are determined by appropriate EA-RWA algorithms that we propose. Even though we focus on the optical layer, the presented algorithms can be combined with algorithms designed for IP over WDM networks with grooming capabilities, to further reduce energy consumption.

III. Network Model and Energy Consumption

An optical backbone network consists of the interconnection of OXC switches by pairs of bidirectional links. Each link consists of several optical fibers, where each fiber supports multiple wavelengths. In a WDM optical system a receiver–transmitter pair known as a transponder (TSP) is required in order to receive/transmit the data via optical channels. A TSP is responsible for adapting the signal to a form suitable for transmission over the optical network for traffic originating at a node, and for the reverse operation for traffic terminated at the node.

Signal QoT in optical networks is significantly affected by physical limitations of fibers and optical components that must be accounted for during connection establishment. The only satisfactory method to overcome physical layer impairments is signal regeneration in some appropriately selected intermediate nodes. Since regeneration consumes substantial energy, reducing the number of regenerators used is important for minimizing overall energy consumption.

We represent the network by a graph $G = (V, E)$, where V denotes the set of nodes and E denotes the set of (point-to-point) multi-fiber links. Each link is able to support a set $F = \{1, 2, \ldots, M\}$ of M distinct fibers, and each fiber supports a set $C = \{1, 2, \ldots, W\}$ of W distinct wavelengths.

The link model with one fiber, typically utilized in a wavelength routed network, is presented in Fig 1. The link is divided into spans, which consist of a standard single-mode fiber (SMF) segment, followed by a dispersion-compensated fiber (DCF) segment. The role of the DCF segment is to compensate the dispersion slope of the SMF segment. Also, the optical communication system is pre- and post-compensated by the DCF [dispersion compensation module (DCM)] for negative dispersion against the standard fiber. Using pre-compensation reduces the impact of impairments such as the self-phase modulation, increasing the achievable transmission distance for a given QoT. The cumulated chromatic dispersion is reset to zero using the post-compensation module at each node in order to have the same cumulated dispersion for any channel leaving a node and equal to zero. In this way any channel dropped at any node will have no accumulated chromatic dispersion. At the end of each SMF span there is a double-stage erbium-doped fiber amplifier (EDFA) that is used to compensate for the losses of the preceding fiber span. The length of a span is the distance between two optical amplifiers. Thus, in order to find the number of amplifiers installed in a link, we divide the length of the link by the span length (and round to the next higher integer).

The node architecture (OXC) considered in this paper is illustrated in 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). We have chosen this architecture because of its inherent ability to support the dynamic traffic evolution in a flexible and economic manner. Reconfigurable optical networks present a clear business case for the operators, who do not have to substantially overprovision their network with equipment in order to be able to serve future variations in traffic. The architecture of Fig. 2 is probably the most promising cost-efficient architecture from the operator's perspective, since additional components can be installed on a node that needs to be upgraded, without affecting the already existing transit traffic, thus offering a "pay as you grow" property. In [15], we give a cost comparison among node architectures with

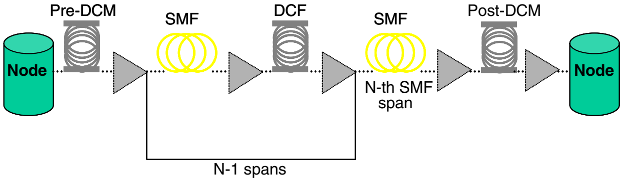

Fig. 1. (Color online) Link model.

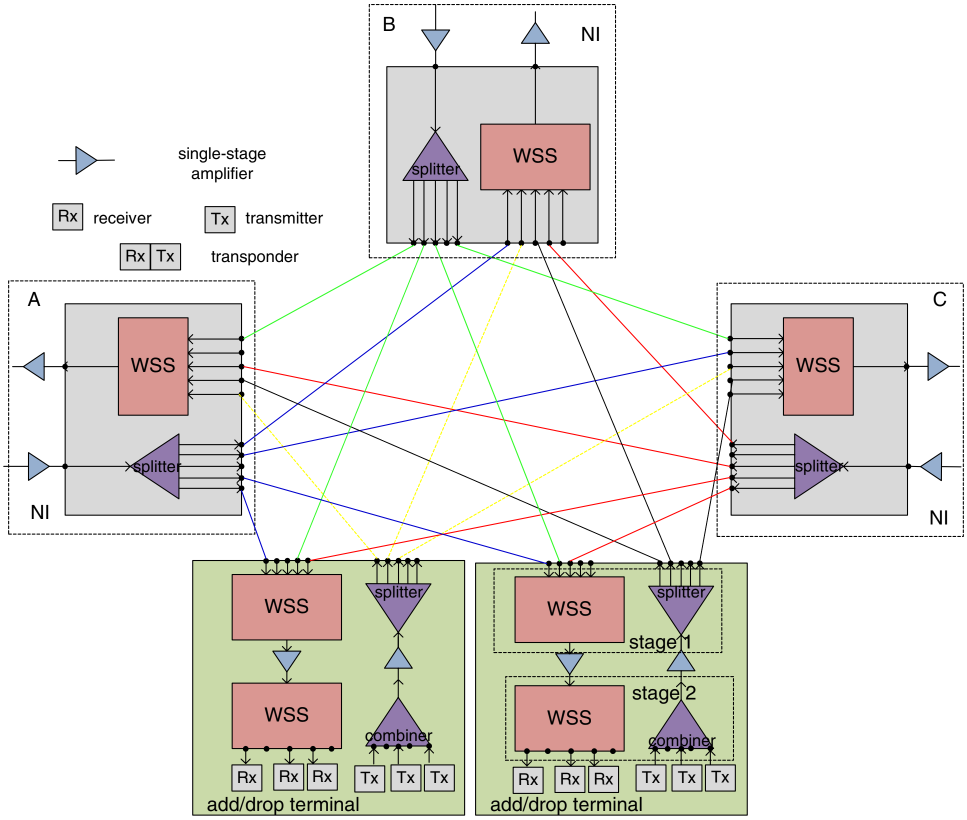

Fig. 2. (Color online) Colorless, directionless, contentionless OXC.

colored/colorless and directed/directionless features, while in [16] we compare these architectures under dynamic traffic demands. These results motivated us to focus on the architecture of Fig. 2 in the present work for the energy-aware planning of optical networks, as it is best able to incrementally support not only current but also future traffic demands.

In this node architecture each add/drop terminal allows a wavelength to be added/dropped only once, and additional terminals are required if we want to be able to add/drop a specific wavelength more than once (contentionless feature). The need to add/drop more than once per wavelength arises when we want to establish more than one lightpath originating from or terminating at the same node and use the same wavelength. The first stage of the add/drop terminal offers the directionless feature of the node. The constraint of this configuration is that only one unique wavelength can be dropped at an add/drop terminal, because a WSS can drop the same wavelength channel only once to its output port. The colorless feature is implemented by the second stage of the add/drop terminal. In that box, a combiner is used to add all the wavelengths and a WSS is used to select which wavelength to drop at which port. Single-stage amplifiers are used between the two stages of an add/drop terminal to compensate for possible losses.

The incoming channels of an NI (for example, box A in Fig. 2) are broadcast, using a splitter, to all other NIs (boxes B and C in Fig. 2). A WSS is connected to the outgoing fiber and can select which wavelength from which other NI or add/drop terminal it wants to add. An NI consists of a WSS, a splitter, and two single-stage amplifiers.

Energy 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., TSPs, regenerators, or number of fibers) required for setting up the lightpaths, and consequently different energy and operational costs. The most power-consuming devices in an optical network are the regenerators, amplifiers (EDFAs), the TSPs, and finally the WSSs that are the building components of the add/drop terminals and NIs.

From an energy perspective, a desired objective is to reduce the number of regenerators and amplifiers used, which in turn depends on the number and length of fibers used, since the distance between amplifiers on a fiber is constant. When multi-fiber links are used, it is important to minimize the number of used fibers per link and turn off inactive (unused) fibers in order to reduce the number of used amplifiers and consequently the network's energy consumption.

By minimizing the number of fibers used, we also minimize the used NIs, which are mainly implemented by WSSs and single-stage amplifiers. Another energy consuming device is the add/drop terminal, which is mainly implemented by WSSs and by single-stage amplifiers. As can be seen in Fig. 3, one way to reduce the number of add/drop terminal is to avoid dropping the same wavelength many times at one node. To describe the technique that we use for

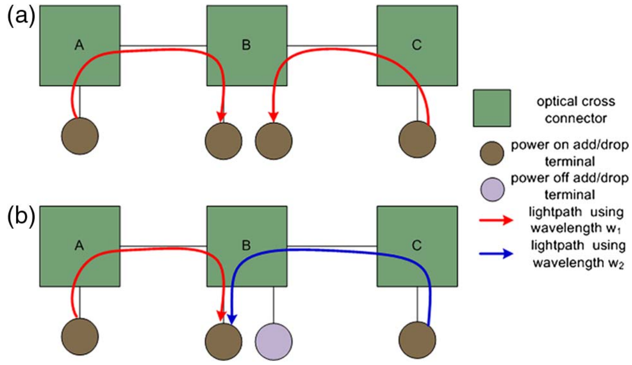

Fig. 3. (Color online) Energy saving by powering off add/drop terminals.

reducing the number of add/drop terminals used during the lightpath establishment of the requested connections, we give a short example. In Fig. 3 there is one established lightpath from A to B and one from C to B. In Fig. 3(a) the two lightpaths use wavelength w_1. This means that we drop the wavelength w_1 to node B twice. Using the architecture of Fig. 2, we need two add/drop terminals in node B for this lightpath. On the other hand, in Fig. 3(b) the two lightpaths are established in different wavelengths, and as a consequence we need only one terminal in node B to drop these wavelengths. Thus the second terminal of node B can be turned off, leading to lower energy consumption. It is clear that appropriate RWA algorithms can be used to prevent adding/dropping the same wavelength many times at a node. Using this technique, the number of required TSPs does not change, because the number of requested lightpaths remains the same.

It is clear from the network model and the discussion presented above that lightpath establishment significantly impacts the power consumption of an optical network. In the next section we present RWA algorithms for selecting the lightpaths to be used for serving the requested traffic that take into account the characteristics of the devices and the techniques mentioned above in order to reduce energy consumption.

IV. Energy-Aware RWA Algorithms

In this section we consider the EA-RWA problem that minimizes the total energy consumed by the active modules in a translucent optical network. In such a network, some connections need regeneration at certain intermediate nodes in order for their QoT to remain above a desired threshold. Two different approaches are proposed. In the first approach the EA-RWA problem is solved to jointly choose the placement of the regenerators and the lightpaths to be used. In the second approach we decompose the problem into 1) a regeneration placement problem and 2) an EA-RWA problem for transparent networks.

The algorithms are given a specific RWA instance, that is, a network topology, the characteristics of its nodes (add/drop terminals, regenerators) and links (amplifiers, fibers), the set of wavelengths that can be used, and a static traffic matrix. The algorithms' output is a plan for the network, consisting of the number and placement of the regenerators and the selection of the lightpaths to be used so as to serve the traffic matrix with minimum energy consumption.

A. ILP Algorithm

For every possible node pair (i,j), $i,j \in V$, we calculate a set P_{ij} of k alternative paths. In general, a value $k = 3$ has been found in our previous work [17] to provide a good balance between the need for near-optimal performance and the need for less algorithmic complexity. Every path is characterized as transparent if its length is lower than a maximum distance, and as non-transparent if its length is larger than that. In our model, a lightpath has maximum transmission reach (distance) equal to D. In general, the maximum transmission reach is selected under a worst case interference assumption, assuming that all wavelengths on all links are fully utilized and calculating the transmission quality of the candidate lightpaths under this assumption. Since the maximum transmission reach accounts for all physical layer impairments, a lightpath chosen in this way is bound to have acceptable transmission quality during its entire duration, even if future connections that interfere with it are established [18]. The following notation is used in order to formulate the problem.

Parameters:

- s, $d \in V$: network nodes
- $w \in C$: an available wavelength
- $p \in P_{ij}$: a candidate path from node i to node j
- $m \in F$: a network fiber

Constants:

- Λ_{sd}: the number of requested connections from s to d
- α_l: the number of amplifiers on link l
- $P_{A/D}$: power consumption of an add/drop terminal
- P_{NI}: power consumption of an NI
- P_A: power consumption of a double-stage amplifier
- P_R: power consumption of a regenerator

Variables:

- x_{pw}: an integer variable that declares the number of connections using path p and wavelength w. This variable may be an integer larger than 1, because our model supports multi-fiber links.
- f_{lm}: an indicator variable, equal to 1 if fiber m is used on link l, and equal to 0 otherwise.
- z_p^{sd}: an integer variable that declares the number of (s,d) connections using (sub-)path p. Path p, which may originate at some node $i \in V$ other than s and terminate at some node $j \in V$ other than t, is a candidate (sub-)path for the connection request (s,d).

Note that the variable x_{pw} may correspond to a lightpath (p,w) that serves transparently an end-to-end demand between the given source s and destination d, or to an intermediate lightpath of a translucent connection that is realized by a series of lightpaths. Variables z_p^{sd} are used to identify the lightpaths that have to be utilized to serve the connection (s,d). The lightpaths identified by the z_p^{sd} variables are realized though specific paths and wavelengths by the corresponding x_{pw} variables.

- y_n: a non-negative integer that denotes the total number of add/drop terminals used at node n.

Objective

Minimize

$$P_{A/D}\cdot\sum_n y_n+\sum_l\sum_m(P_A\cdot f_{lm}\cdot a_l+P_{\mathrm{NI}}\cdot f_{lm})+P_R\cdot\sum_{sd}\sum_p z_p^{sd} \tag{1}$$

subject to the following constraints:

- Incoming traffic constraint:

$$\sum_{p|\text{start from}\,s} z_p^{sd}=\Lambda_{sd},\quad \text{for all }(s,d)\text{ pairs.} \tag{2}$$

- Outgoing traffic constraint:

$$\sum_{p|\text{end at}\,d} z_p^{sd}=\Lambda_{sd},\quad \text{for all }(s,d)\text{ pairs.} \tag{3}$$

- Flow conservation constraint (regenerator allocation):

$$\sum_{p|\text{end at}\,n} z_p^{sd}=\sum_{p|\text{start at}\,n} z_p^{sd},\quad \text{for all }(s,d),\quad \text{all}\,n. \tag{4}$$

- Lightpath assignment constraint:

$$\sum_w x_{pw}=\sum_{sd} z_p^{sd},\quad \text{for all }p. \tag{5}$$

- Distinct wavelength assignment constraint:

$$\sum_{p|l\in p} x_{pw}\le\sum_m f_{lm}\quad \text{for all }l\in L,\quad \text{for all }w\in C. \tag{6}$$

- Number of add terminals per node:

$$\sum_{p\in P|n=s} x_{pw}\le y_n\quad \text{for all }w\in C,\quad \text{for all }n\in V. \tag{7}$$

- Number of drop terminals per node:

$$\sum_{p\in P|n=d} x_{pw}\le y_n\quad \text{for all }w\in C,\quad \text{for all }n\in V. \tag{8}$$

- Non-transparent requests:

$$\begin{aligned} z_p^{sd}=0\quad &\text{for all non-transparent paths }p,\\ &\text{for all }(s,d)\text{ pairs.}\end{aligned} \tag{9}$$

The objective function is chosen as the total energy consumed by the optical fibers, the NIs, the add/drop terminals, and the regenerators that are used. The non-transparent paths in Eq. (9) are those whose physical length is larger than the maximum transmission reach D. Equations (2)–(4) correspond to the lightpath routing constraints, where each connection (s,d) should have node s as the starting node and node d as the ending node, while any intermediate node can be used as a regenerator. Equation (4) ensures that the number of incoming lightpaths at any intermediate node is equal to the number of outgoing lightpaths. Equations (2) and (3) are the corresponding constraints for the origin and termination nodes, respectively, of the lightpaths. Equation (5) assigns paths and wavelengths to the required lightpaths between all node pairs of the network. Equation (6) ensures that each wavelength is used at most once on each fiber. Equations (7) and (8) count the number of add/drop terminals. Equation (9) prohibits the utilization of lightpaths over paths that exceed the maximum transmission reach. The wavelength continuity constraint is implicitly taken into account by the definition of the x_{pw} variable.

B. Decomposition Technique

In the preceding section we described an ILP formulation for the EA-RWA problem in a translucent optical network that jointly makes the regenerator placement and the RWA decisions. This formulation results in large running times, especially for large-sized networks. In what follows, we consider the decomposition of the EA-RWA problem in a translucent optical network into 1) a regeneration placement sub-problem and 2) an EA-RWA in transparent optical networks sub-problem, where each sub-problem is addressed separately and sequentially.

In order to place the regenerators, we follow an approach proposed in [19]. First, we have to identify the connections (s,d) that need regeneration. To do so, we partition the connection requests in the given traffic matrix into a set T of transparent connections and a set $\bar{T}$ of non-transparent connections. A connection (s,d) is characterized as transparent if the length of the shortest path between its source node s and destination node d is lower than the maximum transmission reach D, and is characterized as non-transparent otherwise. For the non-transparent connection requests in $\bar{T}$ we formulate and solve, in phase 1, a virtual topology design problem to decide the intermediate regeneration nodes the non-transparent connection should use. The virtual topology consists of the regeneration nodes with (virtual) links between pairs of transparently connected regeneration nodes. Each virtual link of the paths chosen in the virtual topology to serve a connection corresponds to a sub-connection (lightpath) in the physical topology. Thus, a non-transparent connection is served using two or more consecutive segments (lightpaths), defined by the intermediate regeneration nodes it is going to utilize. Based on these decisions, we transform the initial traffic matrix into a transparent traffic matrix $\tilde{\Lambda}$, where non-transparent connection requests are replaced by a sequence of transparent sub-connection requests. The transparent traffic matrix $\tilde{\Lambda}$ is then used as the input to the EA-RWA algorithm for transparent networks in phase 2. The objective of the regenerator placement algorithm is to minimize the total number of used regenerators. A more detailed description can be found in [19].

In order to make the ILP of the previous section applicable to transparent networks, we omit the variables z_p^{sd} and modify the definition of the variables x_{pw} so as to correspond to paths from the source to the destination and not to (sub-)paths, as in the previous section. The definition of the other variables remains the same. We modify the constraints of the ILP formulation as follows: we omit the constraints in Eqs. (2)–(4) and (9), we preserve the constraints in Eqs. (6)–(8), and we add the constraints

$$\sum_{p \in P_{sd}} \sum_{w} x_{pw} = \Lambda_{sd} \quad \text{for all } (s,d) \text{ pairs},$$

to declare the incoming traffic requirement. Finally, we omit the third term of the objective function, which now becomes

$$P_{A/D} \cdot \sum_n y_n + \sum_l \sum_m (P_A \cdot f_{lm} \cdot a_l + P_{\mathrm{NI}} \cdot f_{lm}). \qquad (10)$$

For large networks and in order to reduce the complexity of the ILP problem, we relax the integrality constraints on the variables x_{pw} and solve the corresponding LP problem using the Simplex algorithm and appropriate techniques to handle the non-integer solutions (e.g., random perturbation, iterative fixing, and rounding [17]). The Simplex algorithm we use moves from vertex to vertex of the feasible polyhedron, and there is a higher probability of obtaining integer solutions than there is using other methods (e.g., interior point methods). This is because it has been observed [17] that in many problems of this type (“multicommodity flow type”), when the coefficients in the constraints are integers, the corners of the feasible polyhedron (which are the ones visited by Simplex) tend to be integers. If Simplex yields non-integer solutions, we continue to increase the number of integer variables in the solutions using a number of techniques. We start by fixing the integer variables, that is, we treat the variables that are integers as final and solve the reduced problem for the remaining variables. Fixing variables does not change the objective cost returned by the LP, so we move with each fixing from the previous solution to a solution with equal or more integer variables that has the same cost. If after successive fixings we reach an all-integer solution, we are sure that it is an optimal solution. However, fixing variables is not guaranteed to return an integer optimal solution if one exists, since the integer solution might consist of different integer values than the ones gradually fixed. When we reach a point beyond which the fixing process does not increase the integrality of the solution, we proceed to a rounding process. When the rounding process is used, the solution obtained is no longer guaranteed to be optimal.

V. SIMULATION RESULTS

In order to evaluate the performance of the proposed EA-RWA algorithms, we carried out a number of simulation experiments. All the RWA algorithms were implemented in MATLAB, and we used the ILOG CPLEX to solve the corresponding (I)LP problems. We compared the performance of the algorithms proposed in Section IV to that of RWA algorithms that do not consider energy minimization criteria, RWA algorithms that partially account for the energy consumption of the network components, and also algorithms that are based on switching off network nodes and links. All the RWA algorithms can be used either in transparent or translucent networks. In the case of translucent networks, we use the decomposition technique of Subsection IV.B for the regeneration placement sub-problem in all the algorithms considered, except for the algorithm that jointly optimizes the regenerators' placement and the RWA (lightpath selection) problems. More specifically, the algorithms we compared in our simulations are the following:

1) **MinW**: The objective of this algorithm is to minimize the maximum number of wavelengths needed to serve the traffic among all links. This is the most common minimization objective used in the RWA problem. The only constraints incorporated in this algorithm are the classical ones of the pure RWA problem (distinct wavelength assignment, traffic, and wavelength continuity constraints). Therefore, MinW constitutes an energy-unaware RWA algorithm.
2) **JEA-RWA**: The objective of this algorithm is to minimize the total energy consumed by all the active modules as described in Subsection IV.A. This algorithm solves the EA-RWA problem in translucent optical networks by minimizing the energy consumed, where the optimization is performed *jointly* over the placement of the regenerators and the selection of the lightpaths.
3) **EA-RWA**: The objective of this algorithm is again to minimize the total energy consumed by all the active modules, and it can be used either in transparent or in translucent networks. In translucent networks, the algorithm breaks the problem into a regeneration placement sub-problem and an EA-RWA for transparent optical networks sub-problem that are sequentially solved.

The following four algorithms try to minimize the energy consumed by the individual modules (fibers, NIs, amplifiers, terminals) that have to be activated to serve the traffic. They have reduced complexity over the JEA-RWA and the EA-RWA algorithms, but they do not minimize the total energy consumption in the network, since each of them concentrates on a single type of device. They give useful insight, however, on the relative significance of each type of device for energy consumption.

4) **MinEF**: The objective of this algorithm is to minimize the extra fibers of the links in a multi-fiber network. We define the term *extra fibers* as the additional fibers required by a network in order to establish a set of

connections when single-fiber links are not sufficient to establish them. This algorithm tries to exhaust the first fiber of the links, and then, if necessary, it uses the other available fibers per link. The use of the first fiber of a link is assumed to add no penalty to the cost objective, but every additional fiber needed to serve the traffic adds some cost to the objective. This algorithm is formulated by the algorithm of Subsection IV.B by setting $P_{A/D} = 0$ in Eq. (10). The objective of the algorithm is, therefore, the minimization of $\sum_l \sum_{m=2}^{M} (P_A \cdot f_{lm} \cdot a_l + P_{\mathrm{NI}} \cdot f_{lm})$.

5) **MinNI**: The objective of this algorithm is to minimize the number of NIs, and it is formulated by setting $P_{A/D} = 0$ and $P_A = 0$ in Eq. (10) of Subsection IV.B. The cost minimized by this algorithm is, therefore, $\sum_l \sum_m P_{\mathrm{NI}} \cdot f_{lm}$.
6) **MinAMP**: The objective of this algorithm is to minimize the number of amplifiers, and it is formulated by setting $P_{A/D} = 0$ and $P_{\mathrm{NI}} = 0$ in Eq. (10) of Subsection IV.B. The cost minimized by this algorithm is, therefore, $\sum_l \sum_m (P_A \cdot f_{lm} \cdot a_l)$.
7) **MinTRM**: The objective of this algorithm is to minimize the number of add/drop terminals, and it is obtained by setting $P_{\mathrm{NI}} = 0$ and $P_A = 0$ in Eq. (10) of Subsection IV.B. The cost minimized by this algorithm is, therefore, $P_{A/D} \cdot \sum_n y_n$.

In order to evaluate the energy consumption of the network planning solutions given by the above algorithms, we have performed simulation experiments both for the small-sized network (Fig. 4) and for the Geant-2 pan-European network (Fig. 8). The span length of each link was set to 80 km, and the bit rate of each connection in these experiments was equal to 10G, in both networks, resulting in a maximum reach of $D = 2500$ km [20]. In Table I we report the values of the power consumption per type of network component [15,21]. The algorithms can also be applied in 40G and 100G systems.

A. Simulation Results for Small-Sized Network

In this section we report the simulation results obtained for the small-sized multi-fiber network of Fig. 4, which consists of six nodes and nine bidirectional links. The link lengths of the network are shown in Fig. 4. Even though the algorithms use ILP formulations, the network size is small and results can be obtained with reasonable running times.

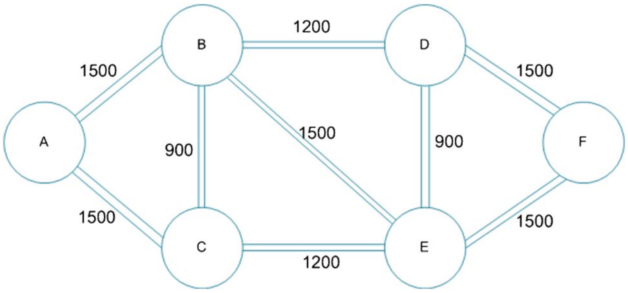

Fig. 4. (Color online) Small-sized network topology used in the simulation experiments.

TABLE I
ENERGY MODEL COMPONENTS

Equipment	Power Consumption [Watts]
Long reach 10G TSP	30
EDFA, double stage	25
EDFA, single stage	15
WSS	40
Regenerator	30

In Fig. 5 we depict the total power consumption of the network for each algorithm as a function of the number of requested connections considering two fibers per link. The total power is computed by multiplying the components that have to be turned on to establish the connections and the power consumed by each component. The worst algorithm in terms of power performance appears to be the MinW algorithm. This is because it tries to minimize the maximum number of wavelengths used per fiber without accounting for the components that contribute to energy consumption. As expected, the JEA-RWA has the best performance, since it jointly minimizes the energy expended by all the power-consuming components without losing the optimum solution, as the decomposition techniques may do. However, we do not lose much of the optimality when using the EA-RWA algorithm, since its performance is quite close to that of the JEA-RWA algorithm. The JEA-RWA algorithm consumes up to 70% less energy than the MinW algorithm, indicating that substantial energy benefits can be obtained at the optical layer by using energy-aware algorithms. The other algorithms minimize the power consumed by specific network components, and their performance lies in between the two extreme cases. Algorithms that partially minimize network components such as MinNI and MinAMP may give different results in the network power consumption, based on the fact that the MinAMP tends to minimize the length of the paths while the MinNI the number of hops. For this reason, variations in traffic may advance one or the other algorithm.

In Fig. 6, we illustrate the power consumed by the network components required when we establish 34 connections in the small-sized translucent network for each

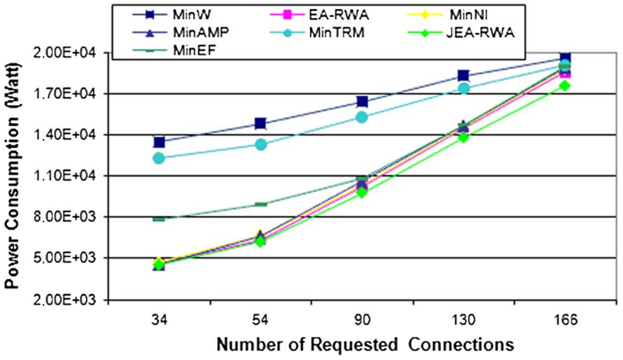

Fig. 5. (Color online) Total power consumption for small network.

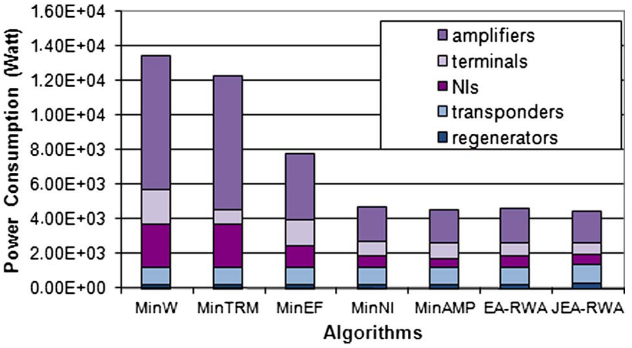

Fig. 6. (Color online) Total power consumption per component type for the different algorithms considered and 34 requested connections.

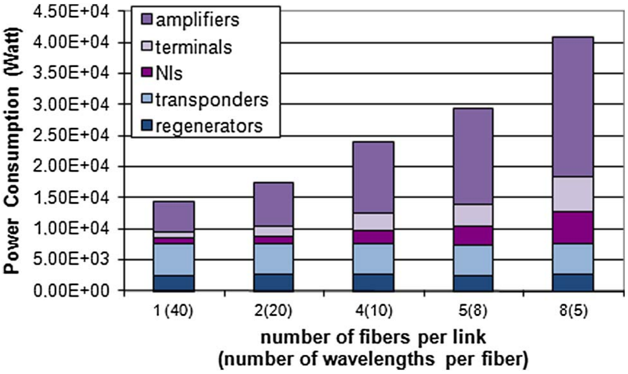

Fig. 7. (Color online) Impact of number of fibers per link in power consumption.

algorithm. The number of used TSPs is the same for all the algorithms and equal to the number of requested demands. Also, the number of the regenerators is the same for all the algorithms considered, since they use the same technique to place the regenerators, except for the JEA-RWA algorithm.

The MinW algorithm uses many more components than the other algorithms considered, while the JEA-RWA and the EA-RWA algorithms use the fewest energy-consuming components. It is evident that each algorithm minimizes mainly the components that are directly related to the minimization objective. Table II shows the percentage of energy saved per component for all the algorithms compared to the energy expended when planning the network using the MinW algorithm, assuming a total of 34 requested connections. Each algorithm saves a different percentage in the consumed energy from different components of the network. The EA-RWA algorithms save energy from all the network components, achieving the maximum minimization. The MinTRM algorithm minimizes only the required terminals. The other algorithms also minimize a combination of the network devices; however, the total power saving is lower than for the EA-RWA algorithms.

In Fig. 7 we show the impact the number of fibers per link has on the network power consumption, using the JEA-RWA algorithm and the case of 166 requested connections. We assume that the number of wavelengths per link remains unchanged and equal to 40 (thus, if we have two fibers per link, then we have 20 wavelengths per fiber, and so on). As can be seen from Fig. 7, when the number of fibers per link increases, power consumption also increases due to the higher number of required amplifiers, NIs, and terminals. This happens because as we keep the total number of wavelengths constant per link, we need more network devices to serve the same amount of traffic (the required wavelengths are the same, but in order to use this number of wavelengths we need more fibers due to the decreased number of wavelengths per fiber).

TABLE II
SAVING OF POWER CONSUMPTION AS COMPARED TO MINW

	Amplifiers	Terminals	NIs
EA-RWA	75%	61%	75%
MinTRM	0%	61%	0%
MinNI	75%	56%	75%
MinAMP	75%	56%	75%
MinEF	50%	28%	50%
JEA-RWA	76%	67%	75%

B. Simulation Results for the Geant-2 Network

We also performed simulation experiments using the Geant-2 network of Fig. 8, which consists of 34 nodes and 54 bidirectional links. All single-hop connections of Geant-2 can be served transparently, but some multi-hop connections are too long, making the use of regenerators necessary. We assumed in the experiments that each link consists of three fibers and each fiber is able to support up to 40 wavelengths per direction. The lengths of the links in the Geant-2 network range between 67 and 2361 km and correspond to the real distances of the network.

In Fig. 9, we present the performance of the MinAMP, the MinNI, the MinEF, and the EA-RWA algorithms when

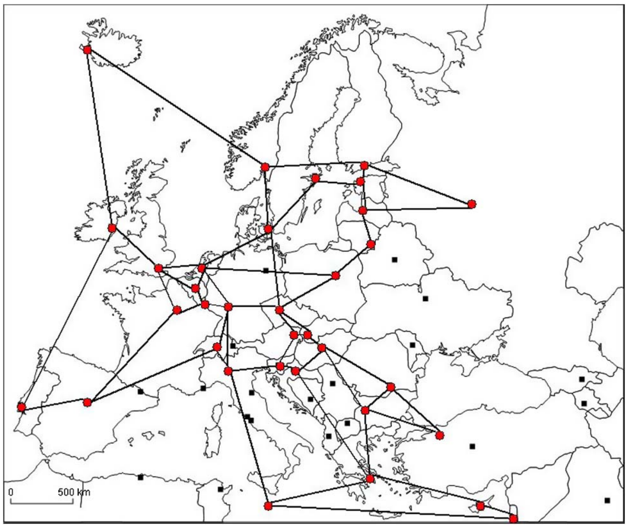

Fig. 8. (Color online) Geant-2 network topology used in the simulation experiments.

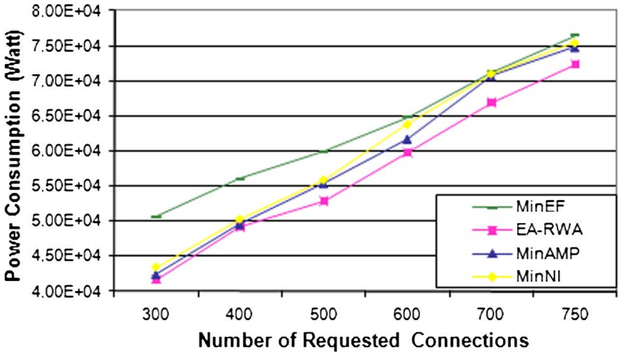

Fig. 9. (Color online) Total power consumption for Geant-2 network.

planning the Geant-2 network. The results were obtained using the LP relaxations of the algorithms, since the corresponding ILP algorithms cannot give solutions for large-scale networks in reasonable times. In order to simplify the figures, we have chosen to exclude from the comparison the algorithms MinTRM and MinW, which exhibited the worst performance.

The EA-RWA algorithm outperformed the other algorithms examined, by consuming up to 18% less power compared to the MinEF algorithm, and up to 6% and 5% less power than the MinNI and the MinAMP algorithms, respectively. The energy savings obtained are more significant for small and medium traffic loads.

Figure 10 illustrates the energy consumed by the network components when 500 connections are established in the Geant-2 network using the MinAMP, the MinNI, the MinEF, and the EA-RWA algorithms. As mentioned before, the number of used TSPs and regenerators is the same for all these algorithms. The EA-RWA algorithm mainly differs in the number of used terminals compared to the MinAMP and MinNI algorithms. As can be seen in Fig. 10, when using the MinAMP and MinNI algorithms the network uses less amplifiers and NIs, respectively, compared to all other algorithms. However, a more sophisticated reduction of power consumption is possible when all the devices are taken into account.

Furthermore, in Fig. 11 we compare the EA-RWA algorithm to an algorithm, to be referred to as the Node-Link-Switch-OFF algorithm, which is based on the previously proposed idea [12,13] that entire nodes and links (but not specific individual modules, as our approach assumes) can be switched off during the operation of a network. This algorithm tries to route every demand using the already switched-on links and nodes. If this is not possible, the algorithm switches on the links and nodes that add the least power in the total power consumption. In these results we assume that the Geant network has one fiber per link and 120 wavelengths per fiber. Figure 11 shows that if we are able to switch off specific components inside a node (or a node when all the components inside it are switched off), we obtain better results than when we are only able to switch off entire nodes. Also, when comparing Figs. 9 and 11, we observe that the network consumes less energy when considering one fiber per link with 120 wavelengths instead of three fibers per link with 40 wavelengths per fiber, which is also consistent with Fig. 7.

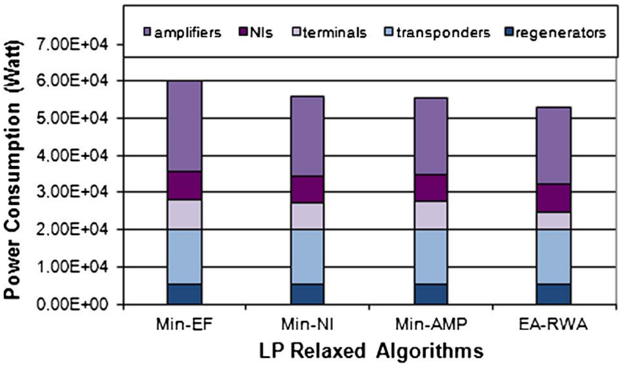

Fig. 10. (Color online) Total power consumption per component for 500 requested connections.

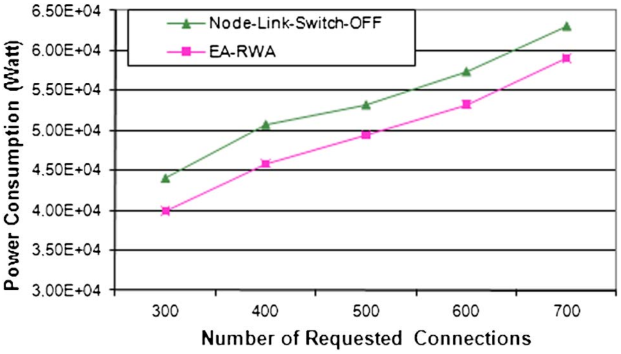

Fig. 11. (Color online) Comparison of the EA-RWA and Node-Link-Switch-OFF algorithms.

VI. CONCLUSION

We presented EA-RWA algorithms that aim at minimizing the energy consumed by the optical layer components when planning translucent optical networks. All the algorithms considered were based on (I)LP formulations that take into account the energy consumed by the various modules (amplifiers, regenerators, add/drop terminals, TSPs, NIs, optical fibers) present in a WDM network. Our results, obtained for a small-sized network and the Geant-2 network topology, show that the proposed EA-RWA algorithms perform significantly better in terms of energy consumption (and corresponding operational expenditure costs) than typical RWA algorithms, indicating that a significant decrease in the total energy consumption can be achieved at the optical layer. Also, we showed the applicability of some of the algorithms considered for networks of large size. Our proposed EA-RWA algorithms for energy optimization at the optical layer can be combined with algorithms presented by other researchers for minimizing the energy consumed at other network layers, so that total network energy minimization can be achieved. Moreover, using these algorithms for efficient energy network design, we also achieve network capital expenditure cost reduction, since these algorithms lead to the usage of fewer network devices.

ACKNOWLEDGMENTS

This work has been supported within the framework of the Action "COOPERATION 2011—Partnerships of Production and Research Institutions in Focused Research and Technology Sectors" of the Operational Programs "Competitiveness and Entrepreneurship" and Regions in Transition (Action's Beneficiary: General Secretariat for Research and Technology), and is co-financed by the European Social Fund (ESF) and the Greek State.

REFERENCES

[1] M. Gupta and S. Singh, "Greening of the Internet," in *SIGCOMM*, 2003, pp. 19–26.

[2] J. Chabarek, J. Sommers, P. Barford, C. Estan, D. Tsiang, and S. Wright, "Power awareness in network design and routing," in *INFOCOM*, 2008, pp. 457–465.

[3] R. S. Tucker, "The role of optics and electronics in high-capacity routers," *J. Lightwave Technol.*, vol. 24, no. 12, pp. 4655–4673, 2006.

[4] R. S. Tucker, R. Parthiban, J. Baliga, K. Hinton, R. W. A. Ayre, and W. V. Sorin, "Evolution of WDM optical IP networks: a cost and energy perspective," *J. Lightwave Technol.*, vol. 27, no. 3, pp. 243–252, Feb. 2009.

[5] G. Shen and R. S. Tucker, "Energy-minimized design for IP over WDM networks," *J. Opt. Commun. Netw.*, vol. 1, no. 1, pp. 176–186, June 2009.

[6] F. Idzikowski, S. Orlowski, C. Raack, H. Woesner, and A. Wolisz, "Saving energy in IP-over-WDM networks by switching off line cards in low-demand scenarios," in *14th Conf. Optical Network Design and Modeling (ONDM)*, 2010.

[7] X. Wang, W. Hou, L. Guo, J. Cao, and D. Jiang, "Energy saving and cost reduction in multi-granularity green optical networks," *Comput. Netw.*, vol. 55, pp. 676–688, 2011.

[8] M. M. Hasan, F. Farahmand, A. N. Patel, and J. P. Jue, "Traffic grooming in green optical networks," in *IEEE Int. Conf. Communications (ICC)*, 2010.

[9] S. Huang, D. Seshadri, and R. Dutta, "Traffic grooming: a changing role in green optical networks," in *Proc. GLOBECOM*, 2009, pp. 5655–5660.

[10] E. Yetginer and G. Rouskas, "Power efficient traffic grooming in optical WDM networks," in *GLOBECOM*, 2009, pp. 1838–1843.

[11] 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 *IEEE GLOBECOM*, 2010.

[12] L. Chiaraviglio, M. Mellia, and F. Neri, "Reducing power consumption in backbone networks," in *IEEE Int. Conf. Communications (ICC)*, 2009.

[13] L. Chiaraviglio, M. Mellia, and F. Neri, "Energy-aware backbone networks: a case study," in *IEEE Int. Conf. Communications (ICC)*, 2009.

[14] R. Bolla, R. Bruschi, F. Davoli, and F. Cucchietti, "Energy efficiency in the future Internet: a survey of existing approaches and trends in energy-aware fixed network infrastructures," *IEEE Commun. Surv. Tutorials*, vol. 13, no. 2, pp. 223–244, 2011.

[15] M. De Groote, K. Manousakis, K. Kokkinos, D. Colle, M. Pickavet, K. Christodoulopoulos, E. Varvarigos, and P. Demeester, "Cost comparison of different translucent optical network architectures," in *Conf. Telecommunications, Internet and Media Techno Economics (CTTE)*, 2010.

[16] K. Manousakis, P. Kokkinos, and E. Varvarigos, "Performance evaluation of node architectures with color and direction constraints in WDM networks," in *Proc. GLOBECOM*, 2010.

[17] K. Christodoulopoulos, K. Manousakis, and E. Varvarigos, "Offline routing and wavelength assignment in transparent WDM networks," *IEEE/ACM Trans. Netw.*, vol. 18, no. 5, pp. 1557–1570, Oct. 2010.

[18] K. Christodoulopoulos, P. Kokkinos, K. Manousakis, and E. A. Varvarigos, "Impairment aware RWA in optical networks: over-provisioning or cross optimization? (Invited)" *J. Netw.*, vol. 5, no. 11, pp. 1271–1278, 2010, Special Issue on All-Optical Routing.

[19] K. Manousakis, K. Christodoulopoulos, E. Kamitsas, I. Tomkos, and E. A. Varvarigos, "Offline impairment-aware routing and wavelength assignment algorithms in translucent WDM optical networks," *J. Lightwave Technol.*, vol. 27, no. 12, pp. 1866–1877, 2009.

[20] O. Rival, A. Morea, and J. Antona, "Optical network planning with rate-tunable NRZ transponders,," in *Proc. European Conf. Optical Communication (ECOC)*, 2009.

[21] F. Idzikowski, "Power consumption of network elements in IP over WDM networks," TKN Technical Report Series TKN-09-006, Telecommunication Networks Group, TU Berlin, 2009.