Energy-Efficient Algorithms for Translucent WDM Optical Networks

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ABSTRACT

This work considers the problem of power minimization in translucent wavelength division multiplexing (WDM) optical networks. Our objective is to minimize the energy expended in optical WDM networks by reducing the number of power consuming components such as regenerators, amplifiers, add/drop terminals, etc. In particular, an algorithm for solving the Energy-Aware Routing and Wavelength Assignment (EA-RWA) problem in translucent networks based on Simulating Annealing (SA) meta-heuristic algorithm is proposed. Numerical results show that energy-efficient regenerator placement combined with appropriate routing so as to switch off power consuming components can significantly reduce power consumption in the network.

Keywords: optical networks, energy-aware routing and wavelength assignment, energy-minimization.

1. INTRODUCTION

Several studies address the problem of power consumption in optical communication networks. Thorough studies on the energy performance of optical and electronic switching systems were published in [1] and [2]. Recently, several approaches have been proposed for reducing the number of network resources used in IP and Wavelength Division Multiplexing (WDM) networks. These studies include grooming algorithms, optical bypass technologies, and techniques to switch off network elements [1]-[5]. Grooming algorithms try to route low-rate demands through higher-rate lightpaths so as to use a smaller number of network interfaces; optical bypassing tries to avoid Optical-electrical-optical (OEO) conversions that consume power; switching-off elements takes into account the time variations in traffic, in order to reduce network over-provisioning and the number of redundant devices used for fault protection. All these techniques try to route the traffic over a smaller number of network elements and can be used in combination with each other.

This work extends the state-of-the-art by proposing an Energy-Aware Routing and Wavelength Assignment (EA-RWA) algorithm to be used during the planning phase of a network, with the objective to minimize the power consumed in optical networks. A heuristic algorithm combined with a Simulated Annealing (SA) meta-heuristic is proposed to minimize the power consumption of optical WDM networks. The algorithm aims at minimizing the power consumed by the various components of an optical network, such as amplifiers, and wavelength selective switches (WSSs), as well as providing energy–efficient regenerator placement. It is assumed that individual components of a node can be switched off when not used by any lightpath. Our results indicate that significant energy benefits can be obtained at the optical layer provided that appropriate planning algorithms are used.

2. NETWORK AND POWER CONSUMPTION

Power is consumed in a WDM network when lightpaths are activated over the links (fibers) and nodes (OXCs – optical cross-connects) of the network. Different solutions of the RWA problem result into different needs in terms of network equipment (e.g., regenerators, amplifiers, etc.) required for setting-up the lightpaths, and consequently result in different energy and operational costs. The most power-consuming devices in an optical network are the optical amplifiers (e.g., EDFAs) used in fiber-optic links and in the network nodes, the WSSs that are the main building blocks of the OXCs, the transponders (TSPs), and the regenerators (placed in certain locations in the network). The node architecture (OXC) considered in this work is illustrated in Fig. 1a. 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). 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. One way to reduce the number of add/drop terminals is to avoid dropping the same wavelength many times at one node.

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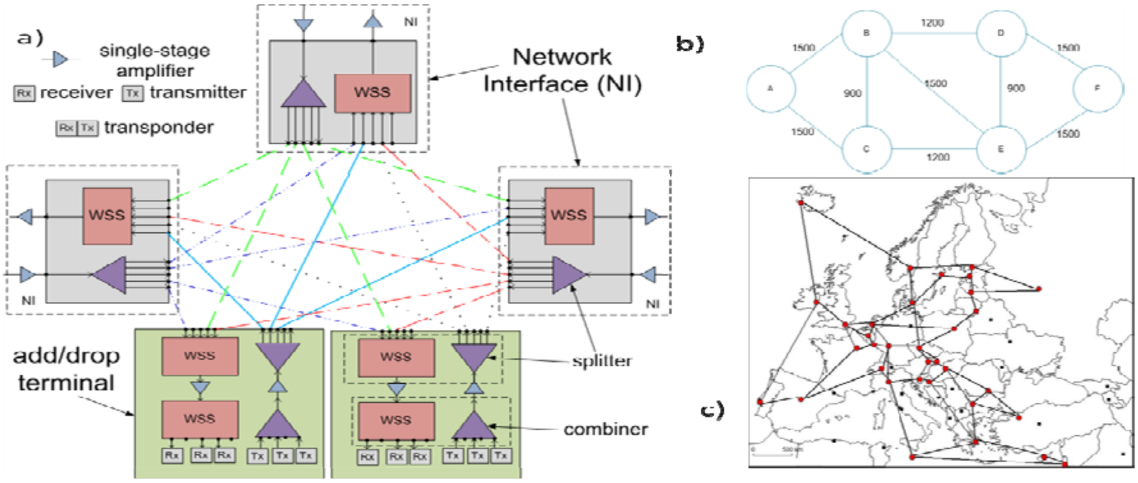

Figure 1: a) Colorless, directionless, contentionless OXC; b) 6-node network; c) Geant-2 network (34 nodes – 54 bidirectional links).

3. ENERGY-AWARE RWA ALGORITHM

The algorithm is given a specific RWA instance; that is, a network topology, the characteristics of its nodes (add/drop terminals, regenerators) and links (amplifiers), the set of wavelengths that can be used, and a static traffic matrix. The proposed heuristic approach consists of three phases. In the first phase, *k* candidate paths are calculated for each requested connection. In the second phase, the demands are ordered according to a Simulated Annealing (SA) meta-heuristic algorithm. Then, in the third phase, a heuristic algorithm is used to sequentially establish the connections while minimizing the power consumption.

3.1 Path Calculation (Phase 1)

In the case of *transparent* networks, *k* candidate paths P_{sd} are identified for serving each requested connection. These are selected by employing the *k*-shortest path algorithm. Every path *p* is characterized as transparent if its length is lower than a maximum distance *D* or non-transparent if its length is larger than a maximum distance (due to physical layer impairments). In the case of a *translucent* network, where some paths need regenerators in order to restore the signal quality, *k* candidate paths are again calculated for each demand (*s*,*d*). Let r_p be the number of regenerators required over path *p*. To identify the number and the placement of regenerators over a path, the algorithm traverses the links of the path starting from the source. The length of the path is kept in a temporary variable that is initialized to zero. For each link it traverses, its length is added, until the temporary length of the path surpasses *D*. At that point, a regenerator is placed at the starting node of the last added link and the temporary length of the path is re-initialized to be equal to the length of that link.

3.2 Simulated Annealing (Phase 2)

The sequential heuristic algorithm establishes connections, one-by-one, in some particular order. Different orderings result in different solutions. To find good orderings, a simulated annealing (SA) meta-heuristic is used, which works as follows. The algorithm starts with a random ordering and calculates the network power consumption (viewed as "energy" in the SA terminology) by sequentially serving the connections, using the heuristic algorithm described in the following subsection (this is the "fitness function" in the SA terminology). For a particular ordering $((s_1,d_1),(s_2,d_2),\ldots,(s_m,d_m))$ of *m* demands, its neighbor is defined as the ordering where (s_i,d_i) is interchanged with (s_j,d_j) for some *i* and *j*. To generate a random neighbor pivots (s_i,d_i) and (s_j,d_j) are chosen uniformly among the *m* demands. This random neighbor creation procedure and the sequential heuristic algorithm (Phase 3) are used as the fitness function in a typical simulated annealing iteration.

3.3 Sequential Heuristic Algorithm (Phase 3)

This section describes the sequential heuristic algorithm, which is the evaluation of the "fitness function" used by the SA algorithm. Each link *l* of the network is characterized by a Boolean wavelength availability vector $\overline{w_l} = (w_{l1}, w_{l2}, \ldots, w_{lW})$, whose i^{th} element w_{li} is equal to 0 if the i^{th} wavelength of link *l* is utilized by a connection, and equal to 1, otherwise. The wavelength availability vector of a path *p* consisting of links $l \in p$ is defined as follows:

$$\overline{W_p} = [W_{pi}] = \underset{l\in p}{\&}\, \overline{w_l} = [\underset{l\in p}{\&}\, w_{li}], \tag{1}$$

where “&” denotes the Boolean AND operation. Thus, the element W_{pi} is equal to 1 if wavelength w_i is available for transmission over path p, and equal to 0 otherwise. The above equation enforces the wavelength continuity constraint among the links comprising a path.

Assuming that the path p uses z regenerators, then the availability vector of path p consisting of links $l \in p$ is defined as follows:

$$\overline{W_p^z} = \left(\overline{W_{p(s-r_1)}};\overline{W_{p(r_1-r_2)}};\ldots;\overline{W_{p(r_z-d)}}\right), \tag{2}$$

where $\overline{W_{p(r_i-r_j)}}$ is defined by equation (1) as the segment of the path between nodes (n_i,n_j) where the regenerators (r_i,r_j) are placed. Note that each regenerator is capable of performing wavelength conversion if desired. Thus, the wavelength continuity constraint must be satisfied only for each regeneration segment of path p.

3.3.1 Phase 3.1: Computing the Candidate Lightpaths

The connections are sequentially established one-by-one in the form of lightpaths. The demands are served according to the order defined by the SA algorithm. In order to establish Λ_{sd} lightpaths for each (s,d) pair under the current utilization state of the network, the algorithm calculates the wavelength utilization vectors $\overline{W_p}$, $\overline{W_p^z}$ of the paths $p \in P_{sd}$, using equations (1) or (2), respectively. Each nonzero element of $\overline{W_p}$ corresponds to a candidate lightpath. Moreover, in the case of a path that contains regenerators, each segment of the path should have at least one non-zero element. Finally, the algorithm chooses the lightpath (p,w) according to an optimization policy.

3.3.2 Phase 3.2: Optimization Policy: Lowest Power Consumption (LPC)

For each candidate lightpath (p,w) the algorithm calculates the excess power consumed by the network. The lightpath with the lowest power consumption is chosen. The excess power consumed by the network is computed using the following equation:

$$P_{total}^{sd} = P_{TSP} + AD_s^i \cdot P_{A/D} + AD_d^j \cdot P_{A/D} + \sum_{l\in p}\sum_{n\in V} NI_n^l \cdot P_{NI} + \sum_{l\in p} P_A \cdot f_l \cdot a_l + r_p \cdot P_{TSP} + AD_s^i \cdot P_{A/D} + AD_d^j \cdot P_{A/D}$$

where P_{TSP}, $P_{A/D}$, P_{NI} , and P_A are the power consumption of a transponder, an add/drop terminal, a network interface, and an amplifier, respectively. Also, AD_n^k is a variable that is equal to 1 if the k^{th} add/drop terminal in node n is not used before the establishment of lightpath (p,w), and 0 otherwise. Similarly, NI_n^l is a variable that is equal to 1 if network interface (Fig. 1a) at node n that is directly connected with link l is not used before the establishment of lightpath (p, w), and 0 otherwise. Finally, a_l is the length of link l, r_p is the number of used regenerators over path p, and f_l is a variable that is equal to 1 if link l is used and 0 otherwise.

4. PERFORMANCE RESULTS

A number of simulation experiments were carried out to evaluate the performance of the proposed EA-RWA algorithm. In order to evaluate the power consumption of the network planning solutions given by the algorithms, simulation experiments were performed both for the 6-node network of Fig. 1b and for the Geant-2 Pan-European network of Fig. 1c.

Table 1 reports the power consumption for different values of the load (number of requested connections) and the different algorithms for the 6-node network topology (Fig. 1b) and for W=80 available wavelengths per fiber-optic link. The total power is computed by multiplying the components that have to be turned on to establish the connections with the power consumed by each component. In particular, the performance of the heuristic algorithm using the simulated annealing meta-heuristic (SA) with 100 iterations (100 corresponds to the different orderings that are examined) for translucent networks was examined, against the k shortest path and First Fit (FF) wavelength assignment algorithm and an optimal Integer Linear Programming (ILP) algorithm [4]. Since the FF algorithm is an energy-unaware algorithm, the differences reported here for FF and LPC are indicative of the energy performance improvements that can be obtained using energy-related parameters in the optimization. The values of the power consumption for each network component are the values used in [4] (e.g., the power consumption of the EDFAs, WSSs, TSPs, and regenerators are 25, 40, 30, and 30 Watts, respectively).

From Table 1 it is obvious that the FF heuristic algorithm has the worst performance in terms of power consumption. Since the algorithm does not account for energy-related parameters, no performance improvement is observed when using the simulated annealing (SA) meta-heuristic. The power consumption was reduced by up to 40.6% for light loads when using the LPC heuristic algorithm compared to the FF heuristic. Moreover, the performance of the LPC is further improved when SA with 100 iterations is used. The performance of the proposed heuristic is quite good, and was able, in most cases, to find solutions with power consumption equal to that reported by the optimal ILP algorithm. The optimal ILP algorithm could not track solutions for large network instances due to high memory requirements (a PC with 4GB memory was used) and for this reason the SA-LPC algorithm is a good alternative as seen from the results of Table 1. For heavy loads, the power consumption improvements reported were smaller than in the case of light loads, but still quite substantial (of the order of 14.5% between the FF and the SA-LPC). It is also important to note that for heavy loads the SA-LPC provides increased performance compared to the energy-unaware alternatives, further highlighting the importance of the proposed approach.

Algorithms	FF	SA-FF	LPC	SA-LPC	ILP
Load	**Power Consumption (Watt)**				
54	12920	12810	7670	7610	7610
90	14540	14430	9350	9290	9250
130	16400	16290	11270	11150	11150
166	18020	17910	13170	12830	12830
210	19830	19830	15150	15030	14810
248	21740	21740	16830	16830	16610
288	23480	23370	19650	19220	18700
322	25100	24990	22450	21445	20730

Table 1. Performance of algorithms for 6-node network.

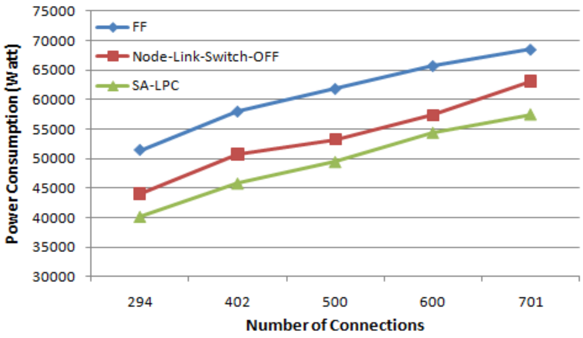

Figure 2. Power consumption for Geant-2 network.

Simulation experiments were also performed using the Geant-2 network of Fig. 1c, 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. In the simulations it was assumed that each fiber is able to support up to 120 wavelengths per direction. The lengths of the links in the Geant-2 network range between 67-2361 km and correspond to the real physical distances of the network. In Fig. 3, a comparison is illustrated for the SA-LPC versus the FF algorithm and versus an algorithm referred to as the Node-Link-Switch-OFF algorithm, that is based on previously proposed work [5] that assumes that entire nodes and links (but not specific individual modules, as our approach assumes) can be switched off during the operation of a network. Figure 3 shows that, if it is possible to switch off specific components inside a node (or an entire node when all the components inside it are switched off), better results are obtained than when only entire nodes are able to be switched off. Specifically, the SA-LPC algorithm outperformed the rest of the algorithms examined, by consuming up to 21% less power compared to the FF algorithm, and up to 9% less power compared to the Node-Link-Switch-OFF algorithm for light loads and up to 17% and 5.5% for heavy loads, respectively.

5. CONCLUSIONS

An EA-RWA heuristic algorithm was presented that aims at minimizing the power consumed by the optical layer components when planning translucent optical networks. The EA-RWA algorithm considered takes into account the power consumed by the various network components (amplifiers, regenerators, add/drop terminals, transponders, network interfaces) present in a WDM network. Our results obtained for a 6-node network show that the proposed EA-RWA heuristic performs similar to an ILP algorithm and results obtained for Geant-2 network show that the proposed EA-RWA heuristic performs significantly better in terms of power consumption than an energy-unaware and a typical Node-Link-Switch-OFF RWA algorithm. These results indicate that a significant decrease in the total power consumption can be achieved at the optical layer.

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