Dynamic Power-Aware Routing and Wavelength Assignment for Green WDM Optical Networks

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Abstract—This paper proposes a novel power-aware routing and wavelength assignment (PA-RWA) algorithm to be applied to a transparent wavelength division multiplexing (WDM) optical network. The proposed algorithm aims at improving the energy efficiency of the optical network by leaving unused optical fibres as much as possible in order to minimize the number of optical amplifiers kept active in the network. A dynamic lightpath establishment scenario is considered and results are compared with other routing algorithms showing that the proposed algorithm can drastically reduce the power consumption for any value of traffic load.

Index Terms—WDM, Power Aware Routing and Wavelength Assignment, Energy Saving, Green Networks.

I. INTRODUCTION

In the last years, the energy consumption issue has been raised as the most critical drawback for the growth of the Internet [1]. Even if the most part of energy is consumed by electronic devices [2], [3], the energy absorbed by the optical network layer is expected to grow as the traffic increases [4] and it can reach several hundreds of kilowatts for wide area all-optical networks [5].

In order to improve the network energy efficiency, different approaches have been proposed aiming at reducing the power consumption of transparent wavelength routed networks [4]-[7]. In particular, as far as the specific problem of the Power Aware Routing and Wavelength Assignment (PA-RWA) is concerned, it was faced for the first time in [7] where two heuristic algorithms were proposed to solve it considering a static traffic scenario; in [7] the basic idea is to minimize the number of optical fibres and nodes used to route lightpaths. At our best knowledge, no other PA-RWA algorithm has been proposed so far.

The present work proposes a novel PA-RWA algorithm, called Load Based Cost (LBC), that can be applied to a dynamic traffic context where the traffic demand is not known in advance. We propose a routing algorithm taking into account both the power consumption of optical transmission links and their congestion. Such an algorithm is based on a cost function that takes into account both the power state and the load of each fibre composing a link. Moreover, a modified version of the First Fit (FF) wavelength assignment algorithm is proposed to further improve the power efficiency of the RWA mechanism.

We compare LBC performance with those arising from three different alternative algorithms: the so called Most Used Path (MUP), proposed in [7], able to be applied to a dynamic scenario, and two classical routing algorithms Least Congested Path (LCP) and Shortest Path (ShP). Finally, the impact of the traffic load on the algorithm performance is investigated.

The rest of this paper is organized as follows. Section II describes the WDM network model and provides the power consumption model for optical nodes and links. In Section III algorithms considered in this work are presented and our proposal is described. Finally, Section IV presents the performance evaluation study.

II. NETWORK MODEL

A transparent circuit-switched WDM optical network with multi-fibre links composed of F fibres for each direction (F>0) is considered. Wavelength conversion is not available in the network, so wavelength continuity is assumed for lightpaths.

The considered optical node architecture is depicted in Fig. 1; it is composed of: i) an electronic control system (ECS); ii) a 3D Micro Electromechanical System (MEMS) based optical switching matrix; iii) a set of transponders on client interfaces; iv) a pair of passive optical MUX/DEMUX for each line interface composed of a couple of input/output fibres.

Figure 1. Optical node architecture

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The total power consumption of a node $i$ can be modelled as follows.

$$P_{\text{Node}}^i(N_i, I_i, W) = P^{\text{ECS}} + I_i P^{\text{Prev}} + N_i W + P^{\text{MEMS}}. \tag{1}$$

In (1), $P_{\text{Node}}^i$ is the total power consumption of the node $i$; $N_i$ is the number of ingoing/outgoing fibres pair; $I_i$ is the number of client interfaces and $W$ is the number of wavelengths of each fibre. $P^{\text{ECS}}$ is the power absorbed by the ECS; $P^{\text{MEMS}}$ is the power absorbed by a single element of the node switching matrix; finally, $P^{\text{Prev}}$ is the power absorbed by a transponder associated to each client interface. It has to be noted that the power consumption of 3D MEMS-based switching matrixes linearly grows with the number of input/output port pair since two mirrors, and an electronic circuitry responsible for their correct space positioning, are placed for each of them.

Each network link is composed of a number of optical fibres; pre and post Erbium Doped Fiber Amplifiers (EDFAs) are deployed at the two ends of each fibre and a number of In-Line Amplifiers (ILAs) are placed along it. So, the power consumption $P_{\text{Fiber}}^{i,j}$ associated to each fibre of the link $i,j$ can be written as:

$$P_{\text{Fiber}}^{i,j}(L_{ij}) = \left[ L_{ij} / d^{\text{ILA}} \right] P^{\text{ILA}} + (P^{\text{PRE}} + P^{\text{POST}}). \tag{2}$$

In (2) $L_{ij}$ is the physical distance between nodes $i$ and $j$ and $d^{\text{ILA}}$ the distance between two ILAs; $P^{\text{ILA}}$, $P^{\text{PRE}}$ and $P^{\text{POST}}$ are the powers consumed by the ILA, pre and post amplifiers, respectively. Table I reports the numerical values of the power consumption of devices assumed in this study [3], [4], [8]-[10]; $d^{\text{ILA}}$ has been fixed to 80 km.

As already stressed, we are interested in reducing the network energy consumption in presence of a dynamic traffic scenario, so the values of the network topological variables (number of nodes, number of links, etc.) are assumed to be fixed. With respect to the power consumption of an optical node (1), the control component is fixed and independent of flow routing, whereas, as far as the switching operation is concerned, it has been assumed that the power consumption just depends on the switching matrix dimension and not on its actually utilization; however, due to the low power consumption of MEMS devices (see Table I), their total contribution can be considered negligible. Moreover, the number of active transponders depends on the number of traffic flows entering in the network and it is out of the scope of the PA-RWA algorithm used to set lightpaths. Instead, recalling the power model of a link (2), whenever a fibre is not used on a given link $i,j$, optical amplifiers along it can be considered off and a power equal to $P_{\text{Fiber}}^{i,j}$ will be saved.

### III. RWA ALGORITHMS

The RWA problem has been extensively studied in the literature and a number of heuristic algorithms have been proposed to solve it [11]. Two different scenarios can be defined [11]: the Static Lightpath Establishment (SLE) and the Dynamic Lightpath Establishment (DLE). In case of SLE, classical RWA algorithms aim at minimizing the number of wavelengths needed to support a given traffic matrix; whereas, in DLE, the goal is to minimize the blocking probability. Both the objectives are not consistent with the problem of minimizing the energy consumption. In fact, a class of used algorithms, like LCP, equally distribute the traffic over the network links, whilst others, like ShP, aim at minimizing the number of used wavelength channels by choosing the path with the minimum number of hops.

The present work faces the DLE problem from the energy consumption perspective: the objective is to reduce the energy consumption by minimizing the number of used EDFAs in the network. As explained in the previous section, such a goal can be achieved by using just a subset of fibres deployed in the network.

#### A. Routing algorithms

A new algorithm is here proposed to minimize the power consumption of optical links; it is compared with three different already known alternatives: LCP, ShP and MUP. The first two, LCP and ShP, were not designed to minimize the energy consumption. LCP is one of the most used routing algorithms in wavelength routed networks due to its good performance in terms of blocking probability [11]. ShP is a least cost path algorithm where link costs are proportional to some cost metrics. As in [7], in our study the link power consumption is assumed as cost metric and a cost proportional to the number of optical amplifiers is assigned to each link. Such a parameter is called Power Cost (PC).

The third algorithm here considered is MUP, proposed in [7]. Such an algorithm assigns a link cost equal to zero if at least one wavelength is available on some used fibre of the link, otherwise a cost equal to its PC is assigned. Even if authors applied MUP to a SLE scenario, it can be observed that MUP can be thought as a dynamic least cost path algorithm with an on-off cost function, so it can be also used in DLE scenarios.

The novel routing algorithm here presented is called Load Based Cost algorithm and takes into account both the power consumption and the congestion status of each link. It belongs to the least cost path algorithm class, in which a time variant cost function is used to dynamically assign link costs accordingly to their current load.

The cost $LC_{ij}(t_n)$ associated to the link $i,j$ at the time $t_n$ is computed as follows:

<table>
<thead>
<tr>
<th>Device</th>
<th>Symbol</th>
<th>Power Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic control system</td>
<td>$P^{\text{ECS}}$</td>
<td>150 W</td>
</tr>
<tr>
<td>Switching matrix input/output port pair</td>
<td>$P^{\text{MEMS}}$</td>
<td>107 mW</td>
</tr>
<tr>
<td>Transponder</td>
<td>$P^{\text{Trans}}$</td>
<td>50 W</td>
</tr>
<tr>
<td>Pre-amplifier</td>
<td>$P^{\text{Pre}}$</td>
<td>10 W</td>
</tr>
<tr>
<td>Post-amplifier</td>
<td>$P^{\text{Post}}$</td>
<td>20 W</td>
</tr>
<tr>
<td>In-line amplifier</td>
<td>$P^{\text{ILA}}$</td>
<td>15 W</td>
</tr>
<tr>
<td>MUX/DEMUX (passive)</td>
<td>---</td>
<td>0 W</td>
</tr>
</tbody>
</table>
\[ LC_i(t_n) = PC_i \cdot LF_i(t_n). \] (3)

Wherein: \( PC_i \) is the Power Cost of the link \( i,j \); it takes into account the power dissipation due to the optical amplifiers deployed along each fibre of the link; this term is given by (2) and does not depend on the traffic load; ii) \( LF_i(t_n) \) is called Load Factor of the link \( i,j \) at time \( t_n \). It is computed on the basis of the link state by a cost function composed of an inner function, called Fibre Cost Assignment (FCA) function, computing the Load Factor \( LF_i^k(t_n) \) related to the fibre \( k \), and an outer function, called Fibre Selection (FS) function, that provides the term \( LF_i(t_n) \) related to the whole optical link on the basis of the Load Factor of each fibre. More in detail:

\[
LF_i^k(t_n) = \text{FS}(LF_i^k(t_n), LF_i^{k+1}(t_n),...,LF_i^{K_i,j}(t_n),LF_i^{K_i,j}(t_n)) \]  (4)

\[
LF_i(t_n) = \text{FCA}(LF_i^k(t_n)). \]  (5)

In (5) \( L_i^k(t_n) \) is the load, i.e. the number of used wavelengths of the fibre \( k \) of the link \( i,j \) at time \( t_n \).

With respect to FCA functions, we observed that, by applying a null cost to used fibres, path lengths increase very much dealing to a huge bandwidth waste. Moreover, when fibre loads are high, the probability to find an available wavelength along the whole path rapidly decreases due to the wavelength continuity constraint, determining the need to use an additional fibre, on some links of the chosen path, during the wavelength assignment phase. This points out the need to design a cost function that increases with the load of each fibre. On the other hand, when the fibre load is low, the probability to power off it, i.e. the probability that all lightpaths using that fibre end prior that a new lightpath is established, is high and therefore a higher cost should be assigned to such a fibre in order to avoid its utilization. The previous observations have suggested the definition of a class of functions, called V-Like, composed of two branches: the first decreases for increasing values of load until it reaches a value equal to \( W/2 \); the second increases in the interval \([W/2, W]\). A number of functions have been tested by varying the shape of the two branches; the curve that showed the best efficiency is shown in Fig. 2, where \( W=20 \) is assumed. The general form of \( LF_i^k(t_n) \) is obtained by considering the square and the square root of the load for the decreasing and the increasing branches, respectively. It computes cost as follows:

\[
LF_i^k(t_n) = |2 \cdot L_i^k(t_n)/W - 1|^{\cdot 2 \cdot \text{sign}(2 \cdot L_i^k(t_n)/W - 1)} \]  (6)

As far as FS functions are concerned, many options are possible, e.g. Max(·), Min(·), Avg(·), etc. Here, just results related to Avg(·) are presented since this function showed the best performance among tested ones. FS functions do not consider \( LF_i^k(t_n) \) terms equal to 1, i.e. terms related to unused or fully loaded fibres; if all terms are equal to 1, two cases can be distinct: 1) an unused fibre exists; 2) there are no unused fibres. In the first case the term \( LF_i(t_n) \) is set to 1; in the second case it is set to infinity.

Listing 1 reports the pseudo-code of the proposed routing algorithm.

### B. Wavelength assignment algorithms

A number of heuristic wavelength assignment algorithms, like First Fit (FF), Most Used (MU), Least Loaded (LL), Relative Capacity Loss (RCL), etc., have been proposed in the literature [11]. In particular FF, besides showing good performance in terms of blocking probability, has a low computational complexity and can be easily implemented since requires that each node handles only local information. This makes it the most used wavelength assignment algorithm in both real networks and research papers.

FF simply assigns a sequence number to wavelengths and then chooses the smallest one that results available on the whole path. When applied to a multi-fibre WDM network, FF looks for an available wavelength considering both used and unused fibres. In this way, all fibres of a link are likely to be used prior to choose a higher wavelength. In the present paper, FF has been used with LCP in order to provide an upper bound to the total consumed energy. In fact, since LCP tends to

```java
for (i=0; i<N; i++)
    for(j=0; j<N; j++)
        //for each link in the network
        found=false;
        unused=false;
        for(k=0; k<Ki,j; k++)
            //for each fiber of link i,j
            if(LF_i^k(t_n) == 0)
                unused=true;
            else if (unused)
                if found
                    LF_i(t_n) = compute_link_cost (LC_i, FCA);
                else if (unused)
                    LF_i=\infty;
                else
                    LC_i = PC_i * LF_i;
        }
Listing 1. LBC routing algorithm pseudo-code.
```
equally load network links and FF to use all fibres of a link, it is very likely that all fibres in the network will be used also with relatively low traffic loads.

In order to avoid energy waste, in [7] a modified version of FF was proposed. It works as follows: in the first phase it just considers used fibres; if a block occurs, i.e. an available wavelength cannot be found just considering used fibres, it works as FF. We call the described wavelength assignment algorithm Two Phase-FF (TP-FF) here. We propose a different modified version of FF, called Least Additional Power-FF (LAP-FF), that differs from TP-FF because, when a block occurs in the first phase, the wavelength requiring the minimum amount of additional power is selected.

Finally, when the chosen wavelength is available on more than one fibre of the same link, all previously defined algorithms select the first fibre.

IV. SIMULATION RESULTS

Physical network topologies used in simulations are randomly generated by fixing the number of nodes $N$, the number of wavelengths of each fibre $W$ and the connectivity degree $D=2L/N(N-1)$, where $L$ is the number of network links. Results here presented have been obtained by assuming $N=25$, $W=40$ and $D=0.2$. It can be observed that the nodal degree $K$, i.e. the average number of links for each node, is $K=D(N-1)$.

Network node positions are uniformly distributed across a squared area of 4000x4000 km$^2$. Links between nodes are generated as follows. First, for each node, at most two links are generated by choosing among the shortest ones. Then, other links are added so that two node-disjoint paths are available between every node pair. Finally, other links are added until the connectivity degree reaches a value equal to the pre-fixed $D$ value; such links are chosen so as to minimize the ratio between the physical distance between two nodes and the physical length of the shortest path connecting such nodes.

The network capacity is dimensioned on the basis of the traffic request. The dimensioning process has the objective to determine the number of fibres of WDM links satisfying the constraint on the blocking probability. It can be observed that the number of deployed fibres impacts the energy consumption just when FF is adopted in the network, determining a power consumption increasing with it.

Connection requests are generated as follows. First, for each node pair, the average traffic parameter $F_{s,d}^{Avg}=TF_{s,d}^{Avg}$ is determined according to the following probabilities:

$$\text{Prob}\{f_{s,d}^{Avg} > 0\} = 1/2.$$  \hspace{1cm} (7)

$$\text{Prob}\{x_1 < f_{s,d}^{Avg} < x_2 | f_{s,d}^{Avg} > 0\} = \int_{x_1}^{x_2} dx / \text{Max}_s f_{s,d}^{Avg},$$

$$x_1 > 0; x_2 < \text{Max}_s f_{s,d}^{Avg}. \hspace{1cm} (8)$$

The TF term is a multiplicative factor used to increase the total amount of traffic in the network; Max$ f_{s,d}^{Avg}$ has been fixed to 5 in our simulations. Then, for each node pair, connection requests are generated by means of a Poisson process with parameter $\lambda_{s,d} = F_{s,d}^{Avg} \mu$; the connection lifetime follows a negative exponential distribution with parameter $\mu = 3600\ s$.

The power consumption of the whole network, i.e. considering all active devices, has been evaluated when LCP-FF is used as RWA algorithm; results in Fig. 3. have been obtained considering an average traffic equal to 12.5 Erlang bidirectional between each node pair; i.e. fixing the TF term equal to 10. As it is evident, most of the power is consumed by EDFAs and transponders, about 47% and 52% respectively, with optical switching matrixes and electronic control systems consuming together less than 2% of power. In the following, only the power consumption related to optical links is considered to analyse and compare performance of RWA algorithms presented in section III.

![Fig. 3. Power consumption of different network devices for LCP-FF RWA algorithm.](image)

A. Performance comparison

In order to evaluate the energy consumption of the described RWA algorithms, an average traffic equal to 12.5 Erlang bidirectional between each node pair has been considered. Fig. 4 compares the routing algorithms when both TP-FF and LAP-FF algorithms are applied. It must be outlined that, whilst the absolute values of the power consumption are dependent on the considered E DFA power consumption, the percentage differences among algorithms are not. The percentage power consumption with respect to the upper bound can be observed on the right axis. As it can be expected, LCP consumes much more power than others since it always tries to equally distribute the traffic on all links. LBC shows the best performance with both wavelength assignment algorithms, whilst MUP performs worse than ShP. It can be seen that LBC saves about 46% of energy with respect to LCP and between 29% and 33% with respect to MUP, dependently on the used wavelength assignment algorithm. Instead, when compared with ShP, just a decrease between 5% and 10% of the consumed energy is achieved. ShP, in fact, shows good performance in terms of energy consumption even if it was not designed to achieve this objective. This is due to the fact that, by applying a cost equal to the link PC, ShP aims at minimizing the number of optical amplifiers used in the network; moreover, when multiple fibres are needed for each link, the wasted energy regards only one used fibre of each
On the contrary, MUP does not show good performance even if it was designed to minimize the consumed energy. The main drawback of MUP is that, when at least one fibre on a number of links connecting all network nodes has been used, other links are very unlikely to be used. This is because, when a link with a high load is selected to route a lightpath, it is likely that a block occurs during the wavelength assignment phase, determining the need to power on a new fibre on that link; in such a way the cost of a link is unlikely to return high. In other words, MUP does not take into account that, even if a wavelength is available on some used fibres, the wavelength continuity constraint determines the need to power on new fibres, especially when the path is long and some links support a high load. LBC, instead, takes into account such considerations by means of the increasing branch of the FCA function and prefers to use new links rather than to route a connection on a path much longer than the shortest one.

By observing the distribution of the average number of used fibres for each link, shown in Fig. 5, it can be seen that MUP leaves unused a higher number of links with respect to LBC but, at the same time, it uses much more fibres on some links and never uses just one fibre on a link. For ShP, such a distribution is very similar to LBC one, whilst for LCP it is very tight around its medium value and links are never unused.

By comparing algorithm performance with the upper bound, it can be seen that by applying LAP-FF or TP-FF to LCP a power saving of about 20% can be achieved. Instead, LBC, ShP and MUP allow to reduce the power consumption of about 57%, 50% and 35% respectively. As far as wavelength assignment algorithms are concerned, it can be seen that LAP-FF always outperform TP-FF saving about 6% of energy when LCP, ShP or MUP are used as routing algorithm; instead, when LBC is used, LAP-FF performance is very close to TP-FF one.

It must be pointed out that results presented here are not in contrast with those presented in [7] since different values of traffic load are considered in the two works. In [7], the total amount of traffic in the network is equal to \( N(N-1)/4 \) bidirectional connections, where \( N \) is the number of nodes, resulting in an average traffic load of 0.5 Erlang between each node pair, whilst the number of wavelengths of each fibre is equal to 128.

**B. Impact of traffic load**

In order to evaluate the impact that the amount of traffic treated by the network has on RWA algorithms, a set of experiments have been carried out by varying traffic from 0.3 up to 20 Erlang between each node pair. In order to do this, the TF term has been varied as follows:

\[
TF=2^i; \ i=\cdots,-2,-1,\ldots,4.
\]

By observing results presented in Fig. 6, where routing algorithms are compared with each other for both wavelength assignment algorithms, it can be seen that MUP shows good performance when the traffic load is low. In particular, when TP-FF is used and the traffic load is equal to 0.3 Erlang, MUP reduces the power consumption by a factor of 5 with respect to ShP, that is approximately the same results obtained in [7]. On the contrary, when traffic load increases, MUP power consumption rapidly increases and exceeds ShP one when traffic load reaches 2.5 Erlang. LBC, instead, allows reducing the power consumption for both low and high traffic loads, especially when LAP-FF is used. Moreover, it can be observed that, when the load increases, ShP performance is very close to LBC one; this is due to the fact that, since the number \( F_{ij} \) of used fibres increases, the power reduction opportunity decreases to \( 1/F_{ij} \), as explained in the previous section.

As far as wavelength assignment algorithms are concerned, LAP-FF always outperforms TP-FF leading to a significant improvement until the traffic load reaches high values. More in details, when the traffic load is 0.3 Erlang, the percentage saving of LAP-FF with respect to TP-FF is about 50% for LBC, 20% for ShP and MUP, and 10% for LCP. As the traffic
increases, the power saving decreases and becomes 5% for LBC and 10% for all other algorithms when traffic is 5 Erlang.

V. CONCLUSION

In this paper we addressed the RWA problem for a transparent multi-fibre WDM optical network from the power consumption point of view, considering a dynamic traffic scenario. A novel routing algorithm, called Load Based Cost, was proposed and compared with Least Congested Path, Shortest Path and Most Used Path algorithms. A new modified versions of the FF wavelength assignment algorithm, called Least Additional Power FF, has been defined and its performance compared with another modified version of FF called Two-Phases FF here, proposed in the literature. Moreover, the FF algorithm in conjunction with LCP has been used to provide an upper bound to the consumed energy. The proposed PA-RWA algorithm aims at reducing the power absorbed by optical amplifiers deployed along fibres.

Results showed that the proposed routing algorithm allows to drastically reduce the power consumption for all values of traffic load. In particular, when traffic load is low, LBC performs better than ShP and LCP, showing the same performance of MUP if LAP-FF is used as wavelength assignment algorithm. Instead, when the traffic load increases, a considerable saving is shown with respect to MUP too, whilst ShP performance results very close to LBC one.

Finally, LAP-FF also allows reducing the power consumption with respect to TP-FF especially for medium-low traffic load.

Fig. 6. Power consumption versus traffic load for LAP-FF and TP-FF.