Energy-Aware Multi-layer Flexible Optical Network Operation

Vasileios Gkamas, Konstantinos Christodoulopoulos, Emmanouel Varvarigos
Computer Engineering and Informatics Dept., University of Patras, GR-26504, Rio, Greece
Computer Technology Institute and Press «Diophantus», GR-26504, Rio, Greece
{gkamas, kchristodou, manos}@ceid.upatras.gr

Abstract—**This work studies the energy-minimized multi-layer operation of IP over flexible optical networks, under a dynamic traffic scenario. We extend a multi-layer connection establishment algorithm to jointly optimize the energy consumption of both IP and optical layers. We compare the performance of the proposed energy-aware multi-layer connection establishment algorithm when applied to fixed-grid MLR and flexible optical networks, with that of an energy-unaware solution. We observe that energy savings can be achieved especially at the optical layer, when the proposed energy-aware algorithm is applied to a flexible, as opposed to a fixed-grid MLR optical network, while we also observed a trade-off between blocking probability and energy efficiency in the case of flexible optical networks.**

Keywords— Energy consumption; dynamic network operation; flex-grid; IP over flexible (elastic) optical networks; Routing Modulation Level and Spectrum allocation (RMLSA)

I. INTRODUCTION

As the traffic volume in metro and core networks is forecast to grow at very high rates [1] due to the continuous growth of consumers' IP traffic, a continuous increase in the telecommunications networks' energy consumption is expected [2]. This gives rise to many concerns regarding the limitations that energy consumption may put on Internet growth and its sustainability. Thus, the design of energy-aware algorithms for core and metro telecommunication networks seems to be more imperative than ever.

The most common technology utilized today for establishing connections in metro and core networks is Wavelength Division Multiplexing (WDM). In such systems optical pulse trains are transmitted through lightpaths, that is, all-optical WDM channels that may span multiple consecutive fibers. As WDM optical networks have been proved to be rigid and static in physical terms, flexible (or elastic) [3] optical networks have recently emerged. Flexible networks are based on (i) flex-grid technology that enables the slicing of the spectrum according to the actual needs, as opposed to the rigid granularity of WDM networks and (ii) flexible transponders, also known as Bandwidth Variable Transponders (BVTs), which can tune their transmission parameters, trading off the reach for spectrum, and/or rate and/or energy. Moreover, flexible networks' increased flexibility fits quite well with the dynamic multi-layer network operation envisioned in future transport networks, where the IP and optical networks are operated in a jointly manner.

Energy consumption analysis and minimization of WDM [4], [5], [6] and flexible optical networks [7], [8], [9], is a research issue which has received much attention during last years. In this work, we study the energy-minimized multi-layer operation problem of IP over flexible networks, under dynamic traffic scenarios. To serve demands, we use an energy-aware multi-layer connection establishment algorithm, which is an extension of the algorithm we proposed in [10] to account for energy efficiency. Note that this algorithm was used in [10] for planning purposes, by iteratively applying it to serve all demands of the related traffic matrix. The multi-layer operation problem of an IP over flexible network, consists of the following sub-problems at two layers: the IP-layer Routing (IPR) sub-problem at the IP layer, and the Routing, Modulation Level and Spectrum Allocation (RMLSA) sub-problem at the optical layer. The RMLSA can further be broken into two substituent sub-problems, namely a) Routing and Modulation Level (RML) selection and b) Spectrum Allocation (SA). The proposed energy-aware multi-layer connection establishment algorithm considers jointly the IP and optical layers of an IP over flexible network, by solving in parallel the IPR+RML+SA problems in an energy-aware manner, following a multi-cost routing approach [11].

Using realistic energy consumption and network models, we found that (a) energy savings can be achieved especially at the optical layer, when the proposed energy-aware multi-layer connection establishment algorithm is applied to a flexible, as opposed to a fixed-grid Mixed Line Rate (MLR) optical network, especially at high loads and (b) a trade-off exists between the blocking probability and the energy efficiency observed, when the flexible network is operated according to an energy-aware, as opposed to an energy-unaware algorithm.

The rest of the paper is organized as follows. In Section II the network architecture and problem under investigation are described. The proposed energy-aware multi-layer connection establishment algorithm for IP over flexible optical networks is outlined in Section III, while its performance is evaluated in Section IV. Finally, our conclusions are given in Section V.

II. NETWORK ARCHITECTURE AND PROBLEM DESCRIPTION

We assume a flexible optical network consisting of flex-grid optical switches and flexible transponders. The optical switches function as Reconfigurable Optical Add Drop Multiplexers (ROADMs) employing the flex-grid technology, and support optical connections (lightpaths) of one or a contiguous number of 12.5 GHz spectrum slots. At each optical switch, none, one or more IP/MPLS routers are connected (these routers comprise the edges of the optical domain), while short reach transceivers are plugged to the IP/MPLS routers leading to flexible (tunable) transponders at the ROADMs. A demand is served by a single lightpath or a sequence of lightpaths between IP/MPLS routers, where at each (if any) intermediate IP/MPLS router, the traffic of the demand at hand, can be groomed with traffic of other demands. So, an IP/MPLS router can be: (i) the final destination of demand's packets in the domain, in which case the traffic will be forwarded further towards their final destination, through same or lower level domains attached to that router, or (ii) an intermediate hop, in which case the packets will re-enter the optical network to be eventually forwarded to their domain destination. Note that (a) lightpaths are bidirectional and the transponders used act simultaneously as transmitters and receivers and (b) a sub-path in the network is defined as a lightpath starting and ending at a router, in cases that a demand is served over a multi-hop IP path, that is, by a sequence of lightpaths at the optical layer.

The IP over flexible network is represented by a directed graph G at which we define two types of nodes, IP nodes and optical nodes, and two layers, the IP layer and the optical layer. An IP node represents a modular IP/MPLS router, while an optical node represents a flex-grid optical switch. In the graph, we also define three types of links, inter-layer, optical and virtual links: (a) an inter-layer link connects an IP node with an optical node and represents the use of a (flexible or fixed) transponder (note that we define inter-layer links at both directions), (b) an optical link corresponds to a fiber and connects two optical switches, and (c) a virtual link corresponds to a lightpath that connects two IP/MPLS routers. Figure 1 illustrates the topology of an IP over flexible network.

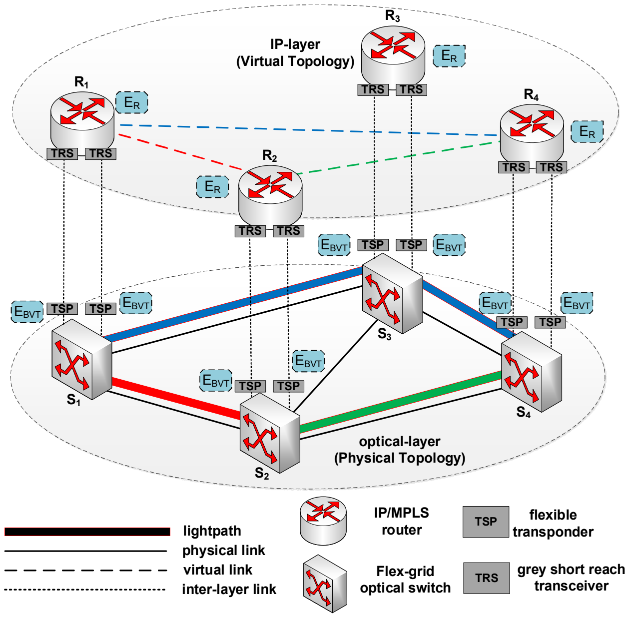

Fig. 1 IP over flexible network architecture

Concerning the IP/MPLS routers, we assume that they are modular and multi-chassis, where each chassis provides a specified number of bi-directional slots with a nominal (maximum) transmission speed. A line-card of the corresponding speed can be installed into each router slot, while each line-card provides a specified number of ports at a specified speed. The flexible transponders used are characterized by transmission tuples [16] that identify the reach at which a transmission is feasible, given the parameters that are under our control. More specifically, the configurations of a flexible transponder of a specific energy consumption e_t are indicated by a set of transmission tuples (d_t, r_t, b_t, e_t), where d_t is the reach at which a transmission of rate r_t (Gpbs) using b_t spectrum slots (including guardband) is feasible with acceptable Quality of Transmission (QoT). Note that the definition of a specific rate and spectrum incorporates the choice of the modulation format of the transmission, while a fixed transponder can be also expressed by a single tuple in the above form.

We assume that at the beginning of network's operation a number of flexible (or fixed) transponders and IP/MPLS routers' line-cards have been installed in the network. These transponders and line-cards can be all or partially idle and configured to serve the initial network traffic. We are given a single demand that corresponds to the IP traffic from a domain adjacent to a router to be forwarded over the optical domain, and our goal is to establish one or more lightpaths, and route the demand over these lightpaths and through possibly intermediate IP/MPLS routers, to the end IP/MPLS router destination, in order to serve the demand. The network is operated by serving each single demand dynamically with the goal of minimizing the energy consumption. As discussed in the introduction, the multi-layer operation problem of an IP over flexible network consists of three sub-problems: the IPR, RML and SA sub-problems. In the IPR problem, we decide on the module(s) (line-card(s) and chassis) to utilize at the source and destination IP/MPLS routers, how to map the demand onto the lightpath(s), and the intermediate router(s) to use to reach the domain destination. In the RML problem, we decide on how to route the lightpath(s) and also we select the transmission configuration(s) of the flexible transponder(s) to be used. Finally, in the SA problem, we allocate spectrum to lightpath(s).

III. ENERGY-AWARE MULTI-LAYER CONNECTION ESTABLISHMENT ALGORITHM

In this section, we describe the energy-aware multi-layer connection establishment algorithm for IP over flexible optical networks that is an extension of the single demand algorithm we proposed in [10]. As stated before, the devised algorithm considers jointly the IP and optical layers and is used to serve dynamically a single demand, by establishing one or more lightpaths and/or grooming the demand over previously established lightpaths, while some of the demands are blocked due to insufficient network resources (spectrum or transponders). The proposed energy-aware multi-layer connection establishment algorithm utilizes a multi-cost routing algorithm to serve a single demand. It takes as input a single demand with source and destination being virtual nodes of network graph G, the demanded rate, the network's topology, the transmission tuples of flexible (or fixed) transponders, the specifications of IP/MPLS routers and the current state of the network (concerning the previous decisions taken on demands). Its goal is to serve the demand and minimize the additive network energy consumption. A demand is split into sub-demands of the supported network rates, and the algorithm is executed many times to select the one that minimizes the energy consumption. The multi-cost algorithm constructs a reduced graph G_A from graph G, which includes all nodes and all links expect for the virtual links (established lightpaths) that have remaining capacity lower than the demanded rate.

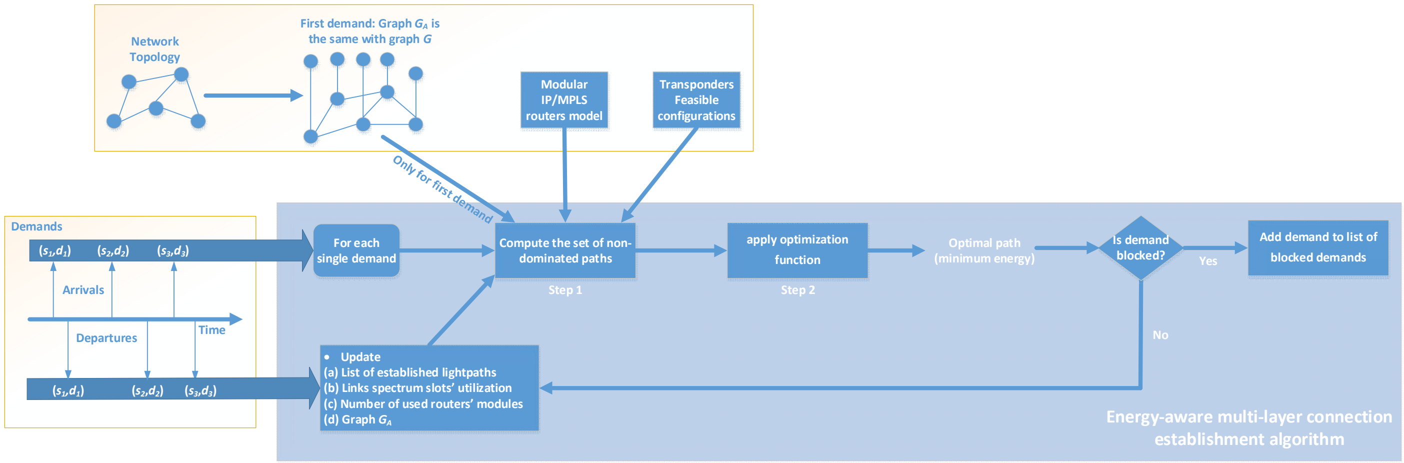

Fig. 2 Block diagram of energy-aware multi-layer connection establishment algorithm

For each type of link (inter-layer, optical and virtual), we define a cost vector that incorporates information regarding both the optical and the IP layers. More specifically, the cost vector of each link of graph G_A incorporates the following parameters:

- An integer variable D_l representing the length of the link. The length of a virtual or an inter-layer link is equal to 0.
- A float variable C_l representing the transponder's energy consumption which is computed according to [12].
- A float variable E_l representing the additive energy consumption of the IP/MPLS router (having as reference its energy consumption up to this point). This variable is non-zero only for an inter-layer link and zero otherwise.
- A vector $\overline{H}_l = \left((r_1, d_1, b_1), (r_2, d_2, b_2), \ldots, (r_m, d_m, b_m) \right)$ whose *i-th* element (r_i, d_i, b_i) records a transmission tuple, where d_i is the feasible reach for rate r_i and spectrum b_i for the specific transponder. These are taken from the transmission tuples of the corresponding flexible (or fixed) transponder that the inter-layer link represents. The vector $\overline{H}_l$ is defined only for a virtual to optical inter-layer link, while it is zero for the other direction (optical to virtual) and other types of links.
- A boolean variable F_l that is equal to 1, if the link is a virtual link, and 0 otherwise.
- A Boolean vector $\overline{W}_l$ of size F (F is the number of spectrum slots) representing the slot availability of the optical links. In particular element $W_{l,i}$ is equal to 1 if the *i-th* slot on optical link l is available and 0 otherwise. For all other type of links (inter-layer and virtual links), the vector has elements equal to 1.

The cost vector $\overline{V}_l$ characterizing a link l is given by:

$$\overline{V}_l = \left(D_l, C_l, \mathrm{E}_l, \overline{H}_l, F_l, \overline{W}_l \right) \quad (1)$$

The proposed algorithm is executed according to a two steps procedure (Figure 2). In the first step, it calculates the cost vectors of non-dominated paths from the source to the destination, by combining the cost vectors of links using a component-wise associative operator that is different for each type of link and each cost component. The algorithm used to compute the set of non-dominated paths is a generalization of Dijkstra's algorithm that only considers scalar link costs. A domination relationship is used to prune the solution space by removing dominated paths that would not be selected by the optimization function (to be applied at the second step). More specific, a path that dominates another path has smaller length, less additive network energy consumption (energy consumption of transponders and additive energy consumption of routers), utilizes fewer virtual links, has higher maximum rate among its sub-paths and has available at least the same spectrum slots. Then, in the second step of the algorithm, an optimization function is applied to the cost vectors of the found candidate paths, which transforms the multi-cost vector into a scalar and selects the optimum path. In our proposed energy-aware algorithm the optimum path is defined as the one with the minimum transponders and routers energy consumption, or in case of tie, the one with the minimum number of virtual links. Of course, other optimization functions can be defined, according to the QoS requirements of the connections.

Taking as reference the algorithm of [10] appropriate changes were made: a) the parameters of links' and paths' cost vectors were replaced with corresponding energy consumption parameters, as described above, b) the domination relationship was defined by taking into account the energy consumption of paths, c) in the optimization function applied at the second step of the multi-cost algorithm, the network cost was replaced by the network energy consumption and d) an additional intermediate policy for selecting sub-paths was defined that takes into account energy minimization.

According to [13], the size of the set of non-dominated paths and consequently the complexity of the multi-cost algorithm depends on the number and type of the cost parameters comprising the cost vector. For the problem at hand, the number of candidate paths is exponential [14], since the cost vector includes the wavelength (slot) utilization and an additive parameter such as the length. However, according to experiments presented in [14] and [15], in realistic networks cases, a high number of non-dominated paths are seldom encountered due to the correlation of the link cost vectors imposed by the wavelength continuity constraint. So the proposed algorithm is expected to have low average running time, a fact that was verified in the experiments with realistic network cases presented in the following.

IV. PERFORMANCE EVALUATION

To evaluate the performance of the proposed algorithm under a dynamic traffic scenario, we conducted various experiments using MATLAB. The demands at each node were generated according to a Poisson process with arrival rate λ requests/time unit and exponentially distributed service times with average $1/\mu=1$ time units (t.u.). Thus λ/μ gives the total network load in Erlangs. The source and destination of a connection were uniformly chosen among all nodes, while the rate requested by each demand is chosen from the set [40, 100, 200, 400] Gbps according to the following probability density functions: [0.5, 0.3, 0.1, 0.1], [0.25 0.25, 0.25 0.25], [0.1, 0.1, 0.3, 0.5], [0, 0, 0.2 0.8], and average rates 110, 185, 274, 360 Gbps, respectively. A total of 5000 demands were served in each experiment.

We assumed two cases of optical networks, a fixed-grid MLR optical network and a flexible (elastic) optical network. We assumed that the fixed-grid MLR network utilizes 40 Gbps, 100 Gbps and 400 Gbps fixed transponders and flex-grid switches to accommodate 400 Gbps transmissions, while the flexible network utilizes a single type of flexible transponders with maximum rate up to 400 Gbps. The simulations were performed for the 12-node generic DT network topology [16], where in the case of the flexible network we assumed that each fiber has available 320 spectrum slots of 12.5 GHz width, while in the case of the fixed-grid MLR network we assumed that each fiber has available 80 wavelengths of 50 GHz width.

TABLE I. TRANSMISSION TUPLES OF FLEXIBLE TRANSPONDERS

Reach (Km)	*Rate (Gb/s)*	*Required Spectrum (in GHz)*	*Energy Consumption (W)*
2500	40	50	155
1800	40	25	155
1700	100	37.5	270
2000	100	50	270
1900	200	75	320
700	200	50	270
1900	400	125	630
700	400	100	432
450	400	75	432

TABLE II. TRANSMISSION TUPLES OF FIXED TRANSPONDERS

Reach (Km)	*Rate (Gb/s)*	*Required Spectrum (in GHz)*	*Energy Consumption (W)*
2500	40	50	155
2000	100	50	270
450	400	75	432

TABLE III. ENERGY CONSUMPTION OF IP/MPLS ROUTERS MODULES

Module	**Energy consumption (W)**
Line Card Chassis	2754
Fabric Card Chassis	7520
Fabric Cards	256
10x40G, 4x100G, 1x400G line-cards	108

The transmission tuples (reach, rate, spectrum, energy consumption) of the used flexible and fixed transponders are shown in Table I and Table II respectively [12]. The energy consumption of a modular multi-chassis IP/MPLS router is computed according to equation (2), assuming that in the case of the flexible network at each router are installed 1x400 Gbps line-cards, while in the case of the fixed-grid MLR network at each router are installed 10x40, 4x100 and 1x400 Gbps line-cards.

$$E_R = \sum_{i=1}^{N} E_{LC}^{i} + N_{LCC} \cdot E_{LCC} + \left\lceil \frac{N_{LCC}}{9} \right\rceil \cdot E_{FCC} + \left\lceil \frac{N_{LCC}}{3} \right\rceil \cdot E_{FC} \quad (2)$$

In equation (2), N is the number of installed line-cards, E_{LC}^{i} is the energy consumption of *i-th* line-card, N_{LCC} is the number of installed line card chassis, E_{LCC} is the energy consumption of one line card chassis, E_{FCC} is the energy consumption of one fabric card chassis and E_{FC} is the energy consumption of one fabric card. The parameter N_{LCC} is computed as

$$N_{LCC} = \left\lceil \frac{C}{K} \right\rceil, \; 2 \le N_{LCC} \le 72, \quad (3)$$

where C is the switching capacity in Tb/s of the modular multi-chassis IP/MPLS router, and K is the capacity of a fully equipped shelf hosting Fabric Cards. Table III shows the energy consumption of the various modules installed at a modular multi-chassis IP/MPLS router (the energy consumption of short reach transceivers, was included in the energy consumption of line-cards installed in IP/MPLS routers).

For our comparison we defined two optimization functions: (a) *Min_S* which minimizes the spectrum used, and (b) *Min_E* which minimizes the network energy consumption. Taking into account the different cases of optical networks and optimization functions defined, we define the following four types of networks: (a) *Flexible-Min_S*: flexible optical network with *Min_S* optimization, (b) *Flexible-Min_E*: flexible optical network with *Min_E* optimization, (c) *MLR-Min_S*: MLR optical network with *Min_S* optimization and (d) *MLR-Min_E*: MLR optical network with *Min_E* optimization. We examined two network scenarios, assuming a large (infinite) or limited number of transponders per optical node and the corresponding number of line-cards/chassis in the IP/MPLS routers. The performance metrics we used for comparing the performance of the aforementioned networks, are the blocking probability, and the average network energy consumption per demand. Note that for the evaluation of the performance of the proposed algorithm, we have taken into account only the dynamic part of the energy consumed in the network, which is proportional to the traffic served, and not the static part of the energy consumed by the IP/MPLS routers, when they are idle.

A. *Infinite number of transponders*

In this section we present the results assuming that at each node there are available infinite transponders, making the spectrum as the sole constraining network resource that can yield to blocking. Figure 3 shows the blocking probability, as a function of the network's load assuming 110 Gbps average rate per demand. We observe that in the case of 100 and 150 Erlangs load, the flexible networks (*Flexible-Min_S* and *Flexible-Min_E*) experience blocking probability equal to zero, while in the case of *MLR-Min_E* network a small number of connections (2 in a total of 5000) are blocked. We also observe that as the load increases, the blocking probability increases, with *MLR-Min_E* network being the one with the biggest increase, and *Flexible-Min_S* network being the one with the smallest increase. More, we observe that regardless the optimization function applied, the flexible network outperforms the MLR networks in terms of blocking probability. This is expected, as the spectrum is more efficiently used in the case of flexible networks, as opposed to fixed-grid MLR networks, due to their finer granular solution for sub- and super-wavelength capacity.

Figure 4 depicts the average network energy consumption per demand, as a function of networks' load in the case of 110 Gbps average rate per demand. We observe that at all cases the biggest contribution to the average network energy consumption per demand is due to the optical transponders. As

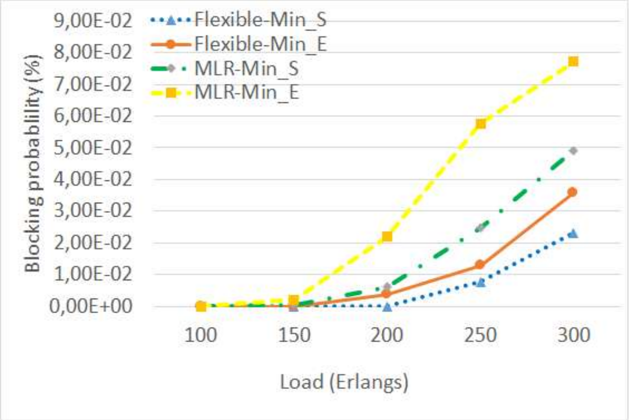

Fig. 3 Blocking probability, as a function of network's load with 110 Gbps average rate per demand

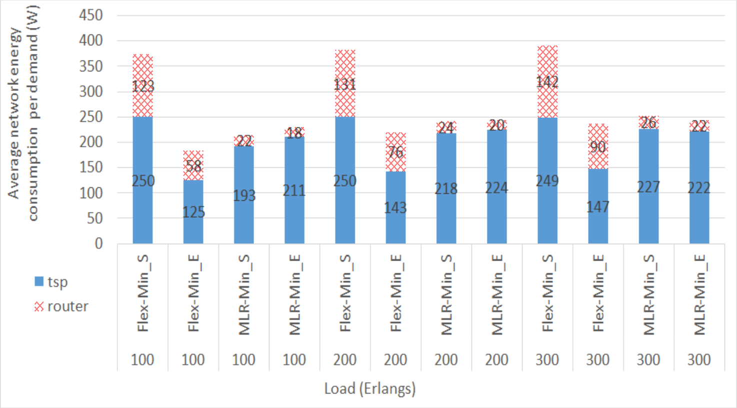

Fig. 4 Average network energy consumption (W) per demand, as a function of network's load with 110 Gbps average rate per demand

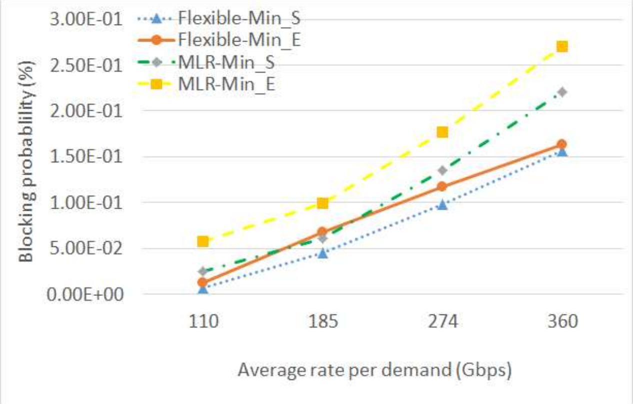

Fig. 5 Blocking probability, as a function of average rate per demand with 2 time units demand average service time

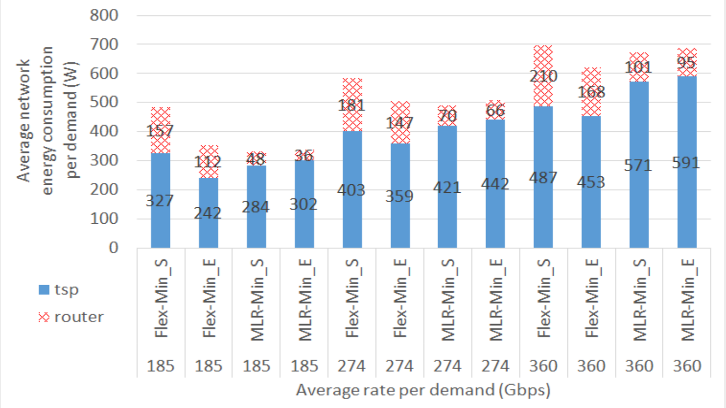

Fig. 6 Average network energy consumption (W) per demand, as a function of average rate per demand with 2 time units demand average service time

we have stated before, we have taken into account only the dynamic part of the energy consumed in the network and not the static one. However, in the case which the static energy consumption of IP/MPLS routers will be included in the calculations, the biggest contribution to the average network energy consumption per demand will be due to the IP/MPLS routers. We also observe that in the case of MLR networks the contribution of routers to the average network energy consumption is smaller, as opposed to flexible networks. This is explained as follows: in the case of MLR networks there are available 10x40, 4x100 and 1x400 Gbps line-cards, so in the case of 40 and 100 Gbps demands, only one line-card must be utilized to connect up to ten 40 Gbps and four 100 Gbps fixed transponders respectively. Instead, in the case of flexible networks where only 1x400 Gbps line-cards are used at the routers, one line-card must be utilized to serve each demand, regardless its required rate. Concerning the average transponders energy consumption per demand, we observe that this is smaller in the case of the *Flexible-Min_E* network, as opposed to MLR networks regardless the optimization function applied, which is expected as the flexible transponders are used more efficiently than the fixed transponders, and they are more energy efficient. Also, we observe that among the four networks cases, the *Flexible-Min_S* network presents the worst performance concerning the average network energy consumption per demand, while it also presents the best blocking probability. This trade-off between blocking probability and energy efficiency, for the flexible network, is explained as follows: The *Flexible-Min_S* network tunes the transponders at the smallest spectrum and consequently rate, and thus uses more transponders since it cannot groom the connections. On the other hand, in the case of *Flexible-Min_E* network less transponders (and consequently line-cards) are used, at higher rate, resulting in better grooming and lower energy consumption. In the MLR network case, this tradeoff is not observed due to the limited number of transmission options (3 transponders). Also, we observe that the average energy consumption of *MLR-Min_S* and *MLR-Min_E* networks are converged, which is explained as follows: in the case of *MLR-Min_S* network, the transmission tuples of the transponders with the minimum spectrum are selected, which are also characterized by minimum energy consumption (as is shown by the transmission tuples of Table II), so the energy consumption of the transponders is also indirectly minimized.

Figure 5 and Figure 6 show the blocking probability and the average network energy consumption per demand as a function of average demand rate and for 2 t.u. average service time. The conclusions derived from Figure 5 are aligned with the ones derived from Figure 3, that is, the flexible optical network exhibit the lowest blocking probability as opposed to the MLR case, regardless of the optimization solution applied. Similarly, in Figure 6, as in Figure 4, we observe again that at all examined cases the biggest percentage of average network energy consumption is due to transponders, while in the case of MLR networks the contribution of routers to the average network energy consumption is smaller, as opposed to flexible networks. Also we observe that at low and medium average per demand rate values (185 and 274 Gbps) the *MLR-Min_S* network exhibits the lowest average energy consumption, and its performance converges with that of the *MLR-Min_E* at high values. At these high average per demand rate values, the *Flex-Min_E* network exhibits the smallest average energy consumption among the four network cases.

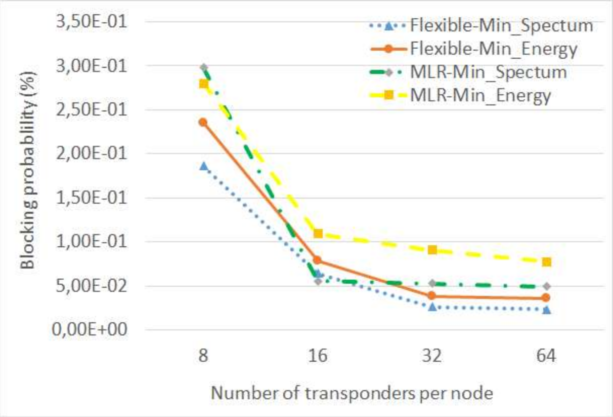

Fig. 7 Blocking probability, as a function of number of transponders per node with 110 Gbps average rate per demand

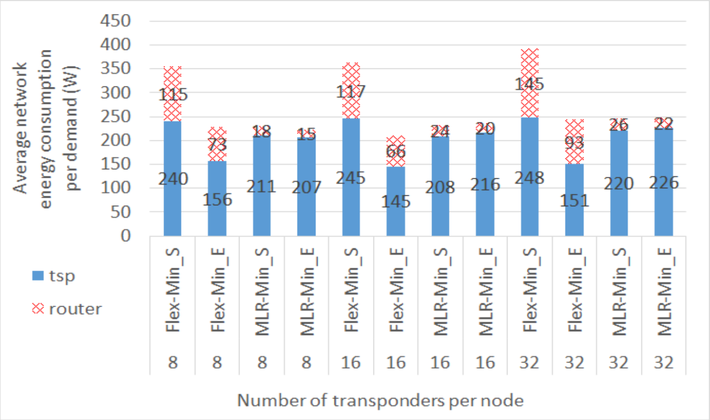

Fig. 8 Average network energy consumption per demand, as a function of transponders per node with 110 Gbps average rate per demand

B. Limited number of transponders

We now present results for more realistic network cases where the network performance is examined as a function of a limited number of transponders available per node. Figure 7 presents the blocking probability for 110 Gbps average rate per demand. As expected, we observe that the blocking probability of demand is reduced as the number of available transponders per node is increased. We also observe that in the case where 8 transponders are available per node, the *Flex-Min_S* network presents the best performance, while the *MLR-Min_S* network presents the worst performance. However, in the case where 32 or 64 transponders per node are available, the *Flex-Min_S* network presents the best performance, while the *MLR-Min_E* network presents the worst performance, which is expected as the flexible transponders used in the case of flexible networks are utilized more efficiently than the fixed transponders used in the case of fixed-grid MLR networks.

Figure 8 shows the related average network energy consumption per demand. We observe that in the case that 16 transponders are available per node, the *Flex-Min_E* network presents the best performance, while in the case that 8 or 32 transponders are available per node, the *MLR-Min_E*, *Flex-Min_E* and *MLR-Min_S* networks present almost equal average energy consumption per demand. Comparing the findings of Figures 7 and 8, we observe again a trade-off between blocking probability and energy efficiency, in the case of flexible networks.

V. CONCLUSIONS

Multi-layer network operation is a complicated but important problem; the joint optimization of the related layers can yield benefits in various optimization parameters. We extended a multi-layer connection establishment algorithm so as to minimize the energy consumption of the network. By evaluating its performance, we concluded that energy savings can be achieved especially at the optical layer, that reach up to 20 %, when the proposed energy-aware multi-layer connection establishment algorithm is applied to a flexible, as opposed to a fixed-grid MLR optical network. Moreover, we observed that the energy efficiency of *MLR-Min_E* and *MLR-Min_S* networks is almost equal. Finally, in the case of a flexible optical network, we observed a trade-off between blocking probability and energy efficiency.

ACKNOWLEDGMENT

This research is partially funded by the European Union and Greek national funds through the EEONPO program of the NSRF action “COOPERATION 2011 - Partnerships of Production and Research Institutions in Focused Research and Technology Sectors” and the ENDECON program.

REFERENCES

[1] “Cisco visual networking index: Forecast and methodology, 2012–2017,” Cisco White Paper, May 2013.

[2] “SMART 2020: Enabling the low carbon economy in the information age,” Global e-Sustainability Initiative Report, Nov. 18, 2008.

[3] O. Gerstel, et. al., "Elastic optical networking: A new dawn for the optical layer?", IEEE Com. Magazine, Vol. 50(2), pp. 12-20, 2012.

[4] M. Hasan, et. al., “Traffic Grooming in Green Optical Networks”, IEEE International Conference on Communications, pp. 1-5, 2010.

[5] Y. Lui, et. al., “Energy-Minimized Design for IP over WDM Networks under Modular Router Line-cards”, First IEEE International Conference on Communications in China, pp. 266-269, 2012.

[6] J. Lorincz, E. Mujaric, D. Begusic, “Energy consumption analysis of real metro-optical network”, 38th International Conference on Information and Communication Technologies, Electronics and Microelectronics, pp. 621-626, 2015.

[7] H. Khodakarami, et. al., “Flexible Optical Networks: An Energy Efficiency Perspective”, JLT, Vol. 32(21), pp. 3958-3969, 2014.

[8] Y. Yiming, et. al., “Virtual topology design scheme with energy efficiency for IP over elastic optical networks”, Chinese Optics Letters. Vol 12(11), 2014.

[9] J. Zhang, et. al., “Energy Efficiency of IP-over-Elastic Optical Networks with Sliceable Optical Transponder”, Optical Fiber Communications Conference and Exhibition, pp. 1-3, 2014.

[10] V. Gkamas, et. al., “A joint multi-layer planning algorithm for IP over flexible optical networks”, Journal of Lighthave Technology, Vol. 33(14), pp. 2965-2977, 2015.

[11] F. Kuipers, et. al., "An overview of Constraint-Based Path Selection Algorithms for QoS Routing", IEEE Communications Magazine, Vol. 40(12), pp. 50-55, 2002.

[12] P. Papanikolaou, et. al., Minimizing Energy and Cost in fixed-grid and flex-grid networks, JOCN, Vol. 7(4), pp. 337-351, 2015.

[13] Z. Wang and J. Crowcroft, “Quality-of-service routing for supporting multimedia applications,” IEEE. J. Sel. Areas Commun., Vol. 14(7), pp. 1228-1234, 1996.

[14] K. Christodoulopoulos, P. Kokkinos, E. Varvarigos, "Indirect and Direct Multicost Algorithms for Online Impairment-Aware RWA", IEEE/ACM Transactions on Networking, Vol. 19(6), pp. 1759 – 1772, 2011.

[15] F. A. Kuipers and P. Van Mieghem, “The impact of correlated link weights on QoS routing”, INFOCOM, pp. 1425-1434, 2003.

[16] IDEALIST project, http://www.ict-idealist.eu/