Multi-period traffic engineering of resilient networks for energy efficiency

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***Abstract*—In this paper we consider the problem of minimizing the energy consumption of IP networks, exploiting the traffic variations over a set of time intervals, while guaranteeing the network QoS and survivability. Energy savings are achieved by putting into sleep mode cards and chassis, when they are not necessary. Network survivability is based on a dedicated protection scheme, wherein a dedicated backup path is assigned to each demand. The multi-period optimization is constrained by inter-period limitations necessary for guaranteeing network stability. Both exact and heuristic methods are proposed. Results obtained with realistic networks operated with flow-based routing protocols (i.e. MPLS) show that up to 60% of the energy savings can be achieved without negatively affecting network resiliency.**

I. INTRODUCTION

Due to Internet rapid expansion, the ICT sector is said to contribute with 2% (0.8 Gt CO2) of annual global greenhouse gas (GHG) emissions [1]. In 2007 the Internet was responsible for 5.5% of the total energy consumption in the world [2]. *Green Networking* aims at optimizing energy consumption of telecommunication networks, by working at different levels, developing energy efficient network devices, methodologies for power aware network design and energy management strategies [3]. The reader is referred to [4] for a discussion on different types of Green Networking proposals. The main issue related to Internet energetic efficiency concerns the fact that, although network utilization varies typically from 5% (night hours) to 50% (peak hours) [5], the network consumption remains practically constant because the energy consumed by network devices is almost independent of the traffic load [6].

In this paper we focus on IP network energy-aware management and we aim at limiting the energy-wise negative effects due to capacity over provisioning, without reducing the QoS and considering protection schemes for ensuring network resilience to failures. We achieve energy savings by assuming that unused devices can be switched off (put into sleep mode). We exploit *Traffic Engineering* (TE) techniques in order to optimize the utilization of the active network infrastructure, guaranteeing at the same time the availability of the resources necessary to provide the network resiliency to single link failures (*Energy and Survivability Aware Traffic Engineering*, ESA-TE). Network survivability requires the use of additional network resources to be used in case of failures. Therefore, there is an obvious trade-off between network resilience and energy efficiency. However, we show that, by optimizing routing and adapting it to traffic scenarios in different time periods, it is possible to achieve remarkable energy savings while guaranteeing protection to failures.

The considered protection scheme makes use of a primal and a backup path that are allocated for each demand (dedicated or 1:1 protection). The latter is used to transmit data only in case of failure of one of the links of the primal path. In order to cope with the management of primary and backup paths, we consider IP networks operated with Multi Protocol Label Switching (MPLS), which lets explicitly select the routes of each individual traffic demand. Routes are optimized according to the traffic scenarios in different time periods.

In particular, we address the problem of minimizing the network energy consumption without affecting the network performance and the efficiency of network management mechanisms. We propose a multi-period optimization problem, where the energy consumption of IP networks is minimized over a set of time intervals, while guaranteeing the network resilience to single link failures (with dedicated path protection) and the service of all traffic demands. Some inter periods constraints to limit the number of device switching-on along the entire set of intervals are used to guarantee network stability and to preserve device lifetime. Two versions of the problem are considered: in the first one the power consumption due to both primary and backup paths is minimized, while in the second one power consumption due to backup paths is neglected, assuming that links can be put to sleep and quickly reactivated only when needed. Actually, in case of failure on the primary path, differently from network nodes, links can be rapidly reactivated implementing a proper signalling mechanism able to promptly detect failures and propagate a wake-up message along the backup paths of all affected flows [7]. Moreover, in order to ensure QoS, we consider two different maximum link utilization thresholds that are used respectively in the case of normal network operation, and when a link failure has occurred. MILP formulations and a heuristic method based on the same MILP formulations are proposed to solve the problem.

The remainder of the paper is organized as follows. In Section II we review previous papers on Green Networking and point out the novelties of our work. In Section III we present the energy management strategy proposed, the system modeling assumptions and the MILP formulations, while in Section IV a new heuristic called *Energy and Survivability Aware Single Time-period Heuristic* (ESA-STH) and based on mathematical programming is proposed. A set of numerical results obtained on five realistic networks are shown and discussed in Section V. Finally, concluding remarks are given in Section VI.

II. Related Work

The problem of reducing Internet energy consumption has been presented in the seminal work by Gupta and Singh [3]. We refer the reader to [4], [8], [9] for exhaustive surveys of the research on the topic, and for accurate taxonomies to classify the different green techniques.

To the best of our knowledge, network energy consumption optimization constrained to survivability requirements has been discussed only in few previous works, that differently from us, focus on the WDM domain [10], [11], [12], [13], [14]. In particular, they deal with the energy-aware management of the lightpaths at the physical optical layer, and aim at putting in sleep mode links and nodes that are unused or that carry only backup paths. An ILP path formulation (based on pre-computed paths) for the energy-aware configuration of lightpaths with dedicated protection is proposed in [11]. Heuristics for the same problem are instead proposed in [10], [13]. A shared protection scheme is instead taken into account by the heuristics proposed in [12], [14]. Our work differs from the previous ones because we consider a multi-period optimization and, above all, we perform the optimization by working at a different level (the IP level). Moreover, we consider two different max-utilization thresholds that account for the two cases when a link failure has occurred or not.

Other works have been instead presented in the field of classic (without protection) energy-aware *TE*, without however considering, except for our previous work on energy-aware multi-period optimization [15], any sort of multi-period optimization. We can classify them according to the routing protocol taken into account. The per-flow routing considered in this paper has been previously adopted in [16], [17]. The approach to off-line energy management proposed in [16] aims at reducing network energy consumption by switching off nodes and interfaces and it is based on a greedy algorithm that considers a single set of traffic demands. Some on-line Energy-Aware Traffic Engineering (EATe) techniques to optimize links and routers power consumption are instead proposed in [17]; these on-line procedures exploit a local search scheme and are based on the assumption that the energy profiles of network devices are strongly dependant on the utilization.

Networks operated with shortest path routing protocols (e.g. OSPF) are instead treated in [18], [19], [20]. The heuristic approaches proposed in [18] and [19] aim at achieving energy savings (by switching off both links and nodes) and minimizing network congestion by efficiently optimizing the link weights. The Energy Aware Routing (EAR) algorithm presented in [20] handles the problem from a totally different perspective, aiming at putting into sleep mode the network elements by using a modified version of the OSPF protocol where neighbouring routers share the shortest path tree.

In addition, some recent contributions that adopt different perspectives: methods for switching off network devices in networks operated with an hybrid routing scheme (MPLS plus OSPF) [21], procedures that turn off network links by only considering network topology features (traffic demands are ignored) [22], a distributed algorithm to determine the operating configuration of each node so as to minimize energy consumption [23].

Finally, we refer the reader to [24] for a general survey on multi-period network optimization and survivable network design.

III. Problem and formulations

A. The MILP formulation

Let us consider an IP network represented by a graph $G(N, A)$, where each router is composed of a chassis and a set of line cards. Router chassis are represented by the set of nodes N. The set of line cards connecting router $i \in N$ and router $j \in N$ is represented by the link (i, j), with n_{ij} line cards installed on link (i, j) ($n_{ij} \geq 1$). We assume the considered daily time horizon to be divided in a set S of time intervals σ, each of duration h_σ. Finally, we consider a set of traffic demands D. Each traffic demand $d \in D$ is characterized by an origin node o_d, a destination node t_d, a nominal value ρ_d, and by a real non negative parameter $r_d^\sigma \in [0, 1]$, that indicates the fraction of the nominal value ρ_d that has to be satisfied during scenario σ.

The target of our optimization is the minimization of the network energy consumption, by putting in sleep mode unnecessary line cards and chassis. Let π_{ij} and $\bar{\pi}$ denote the hourly power consumption of a single card connecting routers i and j, and the hourly power consumption of a chassis, respectively, and let δ represent the chassis energy consumption (normalized with respect to hourly chassis consumption) due to a switching-on. The objective function takes into account the power consumption of cards and chassis, and the power consumption due to the switching-on of the chassis. It can be expressed as:

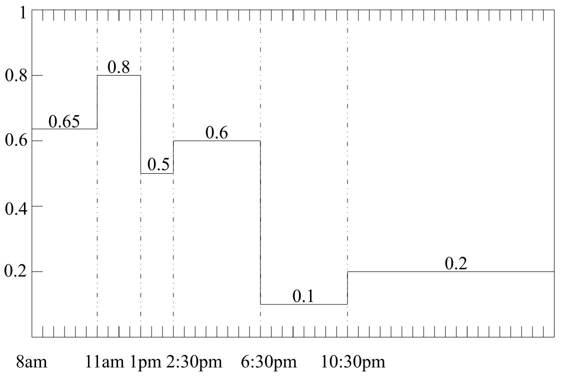

Figure 1. Traffic scenarios.

$$\min \sum_{\sigma\in S} h_\sigma \left(\sum_{j\in N} \bar{\pi} y_j^\sigma\right) + \sum_{\sigma\in S} h_\sigma \left(\sum_{(i,j)\in A} \pi_{ij} w_{ij}^\sigma\right) + \sum_{\sigma\in S}\sum_{j\in N} z_j^\sigma \qquad (1)$$

where y_j^σ are binary variables that are equal to 1 when chassis j is on during scenario σ, w_{ij}^σ are integer variables in $\{0,\ldots,n_{ij}\}$ that represent the number of line cards activated on link (i,j) during scenario σ, z_j^σ are non negative continuous variables, which represent the energy consumption if chassis j is switched on passing from scenario $\sigma-1$ to scenario σ. The power consumed by switching on a chassis is computed through the following constraints:

$$z_j^\sigma \geq \delta\bar{\pi}\left(y_j^\sigma - y_j^{\sigma-1}\right), \forall j\in N, \forall\sigma\in S \qquad (2)$$

Each traffic demand must be routed along two link disjoint paths (MPLS routing), one primary and one backup path. The two paths are described through binary variables x and ξ: $x_{ij}^{d\sigma}$ ($\xi_{ij}^{d\sigma}$) are binary variables that are equal to 1 if the primary path (backup path) of demand d is routed on link (i,j) in scenario σ. Routing variables must satisfy the following flow conservation constraints:

$$\sum_{(i,j)\in A} x_{ij}^{d\sigma} - \sum_{(j,i)\in A} x_{ji}^{d\sigma} = b_i^d \quad \forall i\in N, \forall d\in D, \forall\sigma\in S \qquad (3)$$

$$\sum_{(i,j)\in A} \xi_{ij}^{d\sigma} - \sum_{(j,i)\in A} \xi_{ji}^{d\sigma} = b_i^d \quad \forall i\in N, \forall d\in D, \forall\sigma\in S, \qquad (4)$$

where b_i^d is 1 if $i = o_d$, -1 if $i = t_d$ and 0 in all the other cases. Note that the routing of each demand can vary along the different time intervals. The following constraints guarantee that primary and backup paths of a given demand are link disjoint:

$$x_{ij}^{d\sigma} + \xi_{ij}^{d\sigma} \leq 1, \forall (i,j)\in A, \forall d\in D, \forall\sigma\in S \qquad (5)$$

$$x_{ij}^{d\sigma} + \xi_{ji}^{d\sigma} \leq 1, \forall (i,j)\in A, \forall d\in D, \forall\sigma\in S \qquad (6)$$

The chassis capacity constraints, which force the suitable status of chassis, as well, are expressed as:

$$\sum_{(i,j)\in A}\sum_{d\in D} r_d^\sigma \rho_d \left(x_{ij}^{d\sigma} + \xi_{ij}^{d\sigma}\right) + + \sum_{(j,i)\in A}\sum_{d\in D} r_d^\sigma \rho_d \left(x_{ji}^{d\sigma} + \xi_{ji}^{d\sigma}\right) \leq \psi y_j^\sigma, \forall j\in N, \forall\sigma\in S \qquad (7)$$

where ψ is the chassis capacity. The average value of the fraction r_d^σ of the nominal value ρ_d of demand d that has to be satisfied during scenario σ follows, for all the demands, the profile shown in Figure 1. Both primary and backup paths have an impact on the chassis capacity and on the chassis status.

Two different capacity constraints are imposed w.r.t. link capacity and cards status:

$$\sum_{d\in D} r_d^\sigma \rho_d x_{ij}^{d\sigma} \ \leq\ \mu_a \gamma w_{ij}^\sigma, \forall (i,j)\in A, \forall\sigma\in S \qquad (8)$$

$$\sum_{d\in D} r_d^\sigma \rho_d \left(x_{ij}^{d\sigma} + \xi_{ij}^{d\sigma}\right) \ \leq\ \mu_b \gamma w_{ij}^\sigma, \forall (i,j)\in A, \forall\sigma\in S \qquad (9)$$

Parameter γ is the capacity of one card. The parameters μ_a and μ_b represent the maximum allowed link capacity utilization: μ_a represents the maximum capacity which can be used if no failure occurs, while μ_b represents the maximum capacity which can be used by both primary and backup paths in case of failure. The above constraints force the link cards to be switched on if necessary.

We have to keep active the same number of line cards for both link directions:

$$w_{ij}^\sigma = w_{ji}^\sigma, \forall\sigma\in S, \forall (i,j)\in A : i<j \qquad (10)$$

Since, to guarantee reliability, we do not want to switch on a single line card too many times during a single day (too frequent switching can reduce the card lifetime), we added the following inter-period constraints to limit to a given ε the number of switching:

$$\sum_{k=1}^{n_{ij}} u_{ijk}^\sigma \geq w_{ij}^\sigma - w_{ij}^{\sigma-1}, \quad \forall (i,j)\in A, \forall\sigma\in S \qquad (11)$$

$$\sum_{\sigma\in S} u_{ijk}^\sigma \leq \varepsilon, \qquad \forall (i,j)\in A, \forall k \qquad (12)$$

u_{ijk}^σ are auxiliary binary variables which are equal to 1 if cards k-th linking nodes i and j are powered on in scenario σ. For the sake of completeness we also report the domains of the variables:

$$x_{ij}^{d\sigma}, \xi_{ij}^{d\sigma}, y_j^\sigma, u_{ijk}^\sigma \in \{0,1\}, \quad \forall d \in D, \forall \sigma \in S, \quad \forall (i,j) \in A, \forall k \leq n_{ij} \tag{13}$$

$$z_j^\sigma \geq 0, \qquad \forall \sigma \in S, \forall j \in N \tag{14}$$

$$w_{ij}^\sigma \in \{0, \ldots, n_{ij}\}, \quad \forall \sigma \in S, \forall (i,j) \in A \tag{15}$$

B. The smart consumption MILP model

We consider here a second version of the problem, in which only the line cards energy consumption due to primary paths is considered. Backup paths are used for short period of time, and therefore their power consumption can be considered as negligible. Thus, if only backup paths are routed on a card, such card can be considered as switched off. Concerning the router chassis power consumption, both primary and backup paths must be considered. In fact, as switching on a chassis requires non negligible time, it is not possible to quickly turn a chassis on in case of failure. To model this problem we keep the objective function (1), and constraints (2), (3), (4), (5), (6), (7), (10), (11), (12) and domain constraints as they are. The difference concerns cards status and capacity constraints. The status of cards is forced by constraints (8), while constraint (9) is replaced by

$$\sum_{d \in D} r_d^\sigma \rho_d \left(x_{ij}^{d\sigma} + \xi_{ij}^{d\sigma} \right) \leq \mu_b \gamma n_{ij} y_j^\sigma, \forall (i,j) \in A, \forall \sigma \in S. \tag{16}$$

Constraints (16) guarantee that the capacity on each link is not exceeded by the sum of primary and backup traffic routed on it, when all the cards are switched on. However, the status of cards is forced by primary paths only, as described by (8).

IV. THE SINGLE PERIOD HEURISTIC

Since the two formulations do not allow to efficiently solve at optimality very large instances, we have developed a heuristic algorithm to compute solutions with a limited gap from the optimum. The procedure, called *Energy and Survivability Aware Single Time-period Heuristic* (ESA-STH), aims at minimizing energy consumption of one time interval at a time by solving a MILP model, and it must be repeated for each time interval. The MILP model is formulated as in Section III, but it is applied to a single time interval. When ESA-STH is applied to a new time interval, both the impact of chassis switching on and the constraint on the maximum number of card switching on must be taken into account. Thus, suitable parameters are defined, which represent the state of chassis and the number of transitions to on-state for each card in the previously optimized time intervals. Each time a new time interval is optimized all parameters are updated according to the computed solution and they are used in the modified version of constraints (2), (11) and (12). To guarantee that constraints on card reliability are not violated, if a card has been already switched on ε times in the previously optimized time intervals, it is forced to keep its current status (powered on) for the next time intervals. Since the final solution can vary according to the starting time period, we repeat the procedure using each time interval as the starting one, and then we take the best solution.

Table I
OVERVIEW OF DIFFERENT NETWORK CONFIGURATIONS

case	device	capacity	hourly cons.
–	Chassis Juniper M10i	16Gbps	86.4 W
alfa	FE 4 ports	400 Mbps	6.8 W
delta	OC-3c 1 port	155 Mbps	18.6 W
eta	GE 1 port	1 Gbps	7.3 W

V. COMPUTATIONAL RESULTS

A. Network scenarios

We have tested and compared results obtained by optimizing the MILP formulation and the ESA-STH heuristic for both problems. We used five networks from the SNDLib [25]: *polska*, *nobel-us*, *atlanta*, *france* and *nobel-eu* networks. In each network all routers are assumed to be of the same type. Three different cases, *alfa*, *delta*, and *eta*, which use the same chassis but different types of cards, were considered. Their capacity and consumption are provided in Table I. The network nodes are divided into core and edge routers and for each network a subset of core routers was chosen. Note that core routers are the only ones that can be put in sleep mode, since they are neither source nor destination nodes. As for the traffic matrices, the nominal traffic demand amounts ρ_d have been obtained scaling by a fixed parameter ϖ the traffic matrices provided by the SNDLib; ϖ has been dimensioned in order to obtain a utilization lower than 50% when nominal demands ρ_d are efficiently routed through the full active networks on single paths (link utilization is usually lower than 50% during peak hours [5]). We have generated three different scenarios of traffic for each network, where the r_d^σ parameters (amount of the nominal value ρ_d that has to be satisfied during scenario σ) are randomly selected with a uniform distribution, centered around the mean values illustrated in Figure 1. Finally, we set δ (chassis switching-on normalized consumption) equal to 0.25, ε (switching-on limit) equal to 1, n_{ij} (number of cards in link (i,j)) equal to 2 for each link, μ_a (link max-utilization due to primary paths) equal to 50%, and μ_b (link max-utilization due to both primary and backup paths) equal to 85%.

B. Numerical results

The tests have been carried out on Intel i7 processors with 4 core and multi-thread 8x, equipped with 8Gb of RAM. The models are solved with CPLEX 12.3.0.0. In Tables II we report the average values obtained for each instance using three random traffic scenarios. Columns $|N|$-$|N_c|$, $|A|$, $|D|$ and *equip* represent the number of nodes and core nodes, links, traffic demands and the device type, respectively. We report the results for the basic problem

Table II

COMPUTATIONAL RESULTS: COMPARISON BETWEEN THE EXACT FORMULATIONS AND ESA-STH WHEN EXPERIMENTING WITH *polska*, *nobel-us* AND *atlanta* NETWORKS.

Test						B_{on}				B_{off}				$No-protection$		
						Model		ESA-STH		Model		ESA-STH		ESA-STH		
ID	Net	$\|N\|$-$\|N_c\|$	$\|A\|$	$\|D\|$	*equip*	$\%E_c$	$\%gap_{opt}$	$\%E_c$	$\%gap_{model}$	$\%E_c$	$\%gap_{opt}$	$\%E_c$	$\%gap_{model}$	$\%E_c$	$\%gap_{B_{on}}$	$\%gap_{B_{off}}$
1	polska	12-6	36	15	alfa	71.42	1.34	71.60	0.17	67.83	0.99	68.05	0.22	60.76	-10.66	-7.07
2	polska	12-6	36	15	delta	61.64	3.31	62.05	0.40	55.44	2.00	55.97	0.53	50.95	-10.69	-4.49
3	polska	12-6	36	15	eta	70.80	1.43	71.01	0.21	67.05	1.29	67.30	0.25	60.17	-10.63	-6.88
4	polska	12-3	36	35	alfa	76.65	1.83	76.93	0.28	72.17	2.70	72.16	-0.01	65.64	-11.01	-6.53
5	polska	12-3	36	35	delta	68.29	4.87	68.71	0.43	60.20	4.94	60.20	0.00	56.87	-11.41	-3.33
6	polska	12-3	36	35	eta	76.16	2.41	76.28	0.12	71.39	3.30	71.39	-0.01	65.13	-11.02	-6.26
7	nobel-us	14-7	42	21	alfa	60.78	0.88	60.77	0.00	57.21	0.71	57.38	0.17	49.38	-11.40	-7.84
8	nobel-us	14-7	42	21	delta	51.98	2.56	51.98	-0.01	45.69	1.73	45.95	0.26	40.68	-11.30	-5.01
9	nobel-us	14-7	42	21	eta	60.21	1.16	60.20	-0.01	56.46	0.88	56.61	0.16	48.79	-11.42	-7.67
10	nobel-us	14-4	42	45	alfa	78.13	1.45	77.95	-0.17	74.72	2.71	74.49	-0.23	67.62	-10.51	-7.10
11	nobel-us	14-4	42	45	delta	67.04	3.07	66.65	-0.40	60.96	5.86	60.56	-0.40	56.76	-10.29	-4.20
12	nobel-us	14-4	42	45	eta	77.53	1.69	77.31	-0.23	73.78	2.76	73.67	-0.11	66.88	-10.66	-6.91
13	atlanta	15-8	44	42	alfa	75.37	0.71	75.49	0.13	71.30	1.39	71.38	0.08	59.17	-16.72	-12.13
14	atlanta	15-8	44	42	delta	64.21	1.61	64.56	0.35	55.89	2.85	55.83	-0.06	46.33	-17.88	-9.56
15	atlanta	15-8	44	42	eta	74.67	0.99	74.80	0.13	69.58	1.52	69.66	0.09	55.84	-18.84	-13.74
16	atlanta	15-4	44	110	alfa	78.54	2.12	78.80	0.26	72.98	3.22	72.61	-0.37	67.50	-11.04	-5.48
17	atlanta	15-4	44	110	delta	68.38	3.51	68.44	0.06	60.04	7.99	58.69	-1.34	55.51	-12.87	-4.53
18	atlanta	15-4	44	110	eta	78.12	2.39	78.17	0.05	72.33	3.76	71.72	-0.61	66.89	-11.23	-5.44

(III-A) in column B_{on}, for the variant (III-B) in column B_{off} and for another variant where no path protection is considered in column $No - protection$. For the first two, we report the results obtained by the formulation (Model) and the heuristic (ESA-STH), while for the latter we report only the result computed by ESA-STH: E_c is the energy consumption level of the optimized network (normalized with the consumption of the fully powered on network), gap_{opt} is the gap from the best lower bound known achieved by CPLEX, and gap_{model} represents the gap of the heuristic solution from the solution calculated by solving the MILP model. Finally, columns $gap_{B_{on}}$ and $gap_{B_{off}}$ show, respectively, the consumption gap between the solutions of the variant without protection and those obtained solving the model for the two protected cases. Solving the complete MILP model, CPLEX time-limit has been set equal to 2 hours. Solving the single time periods of ESA-STH, it has been set equal to 1 minute for the smaller instances.

The first observation is that, if the links that carry only backup paths have to be kept active and 50% of routers are core routers (tests 1-2-3-7-8-9-13-14-15), both exact formulations and ESA-STH reduce the energy consumption up to 52% and generally around 65%. We always obtain higher energy savings when we experiment with the *delta* network configuration. This is due to the fact that the ratio between card and chassis consumption for this case is the largest. The optimized energy consumption varies instead from 67% to a maximum of 79% when only 25% of routers are core routers, (Tests 4-5-6-10-11-12-16-17-18) and thus only a very limited number of chassis can be put to sleep. This is not surprising as chassis consumes much more power than cards and for those cases there are fewer chassis to be switched-off.

It is very important to observe that if links of backup paths can be put in sleep mode, we can achieve additional energy savings, with an average increase of 5% with peaks around 8%. In this case, the solutions obtained have the distinguishing characteristic with respect to previous case, that there is a set of links dedicated to the allocation of the main paths, while the others are used to carry only backup paths so that they can be put to sleep. Moreover, the energy consumption increase due to network resiliency (column $No - resiliency$) varies between 10% and 20% when backup links are kept on, and between 4% and 14% when they are switched off. Using two different maximum utilization thresholds allows to route the backup paths on spare capacity installed for the primary ones. Therefore, an optimized management of the routing allows to guarantee resiliency with a very limited increase in the energy consumption.

With both formulations CPLEX provides reasonable gaps w.r.t. the lower bounds, being about 2% on the average and always below 4.94%. However, CPLEX seems to spend most of its time in improving the lower bound in order to prove optimality, thus we believe that the gap w.r.t. the optimal solution may be even smaller. Moreover, the ESA-STH heuristic has proved to be very efficient, as the gaps w.r.t to the optimization models are always below 0.5%. In some remarkable cases, the gap is even negative; this implies that the heuristic results are closer to the lower bound than the ones obtained by CPLEX.

The validity and efficiency of ESA-STH has been finally confirmed by the results obtained on the larger instances (*france* and *nobel-eu* networks). The results reported in Table III, obtained by limiting the CPU time to solve each time interval to 2 minutes, show in fact that the energy savings achieved are very similar to the ones obtained with the smaller networks, and generally around 65% and 60% for the two cases when backup devoted links can or cannot be put to sleep. Moreover, all the observations previously reported remain still valid with the larger networks.

VI. Conclusion

A new energy and survivability aware multi-period traffic engineering problem with inter-periods constraints is addressed in this paper. The aim is minimizing the energy consumption of an IP network following daily traffic variations, while guaranteeing the survivability by applying a dedicated protection scheme. We proposed MILP formulations for two different versions of the problem (where links carrying exclusively backup paths can or cannot be put in sleep mode), and a heuristic method called ESA-STH that finds solutions very close to the optimum with networks of up to 30 nodes. Given its efficiency, ESA-STH can be naturally used to solve much larger instances. We achieve considerable energy savings in both cases, up to 45% when half the routers are in the core. We are currently focusing on improving the efficiency of the formulations and the accuracy of the heuristic, as well as on new inter-periods constraints.

Table III
Computational results obtained by ESA-STH when experimenting with *france* and *nobel-eu* networks.

Test						ESA-STH	
						B_{on}	B_{off}
ID	Net	$\lvert N\rvert$-$\lvert N_c\rvert$	$\lvert A\rvert$	$\lvert D\rvert$	*equip*	$\%E_c$	$\%E_c$
19	france	25-12	90	78	alfa	71.25	69.20
20	france	25-12	90	78	delta	61.38	53.84
21	france	25-12	90	78	eta	72.61	68.19
22	france	25-7	90	153	alfa	78.36	74.67
23	france	25-7	90	153	delta	65.81	59.53
24	france	25-7	90	153	eta	77.47	71.82
25	nobel-eu	28-14	82	91	alfa	72.74	70.36
26	nobel-eu	28-14	82	91	delta	61.15	57.57
27	nobel-eu	28-14	82	91	eta	72.06	69.55
28	nobel-eu	28-7	82	210	alfa	78.05	75.28
29	nobel-eu	28-7	82	210	delta	65.79	60.56
30	nobel-eu	28-7	82	210	eta	77.28	74.25

References

[1] The Climate Group. SMART 2020: Enabling the low carbon economy in the information age. In *2010 State of Green Business*, June 2008.

[2] J.G. Koomey. Estimating total power consumption by servers in the us and the world, 2007. Technical report, February 2007.

[3] M. Gupta and S. Singh. Greening of the internet. In *Proceedings of the conference on Applications, technologies, architectures, and protocols for computer communications*, pages 19–26, 2003.

[4] H. Mellah and B. Sansò. Review of facts, data and proposals for a greener Internet. In *Proc. of Broadnets09*, September 2009.

[5] C. Fraleigh, S. Moon, B. Lyles, C. Cotton, M. Khan, D. Moll, R. Rockell, T. Seely, and S.C. Diot. Packet-level traffic measurements from the Sprint IP backbone. *Network*, 17(6):6–16, 2003.

[6] J. Chabarek, J. Sommers, P. Barford, C. Estan, D. Tsiang, and S. Wright. Power awareness in network design and routing. In *Proc. of INFOCOM 08*, pages 457–465, Phoenix, Arizona, 2008.

[7] Active/idle toggling with 0base-x for energy efficient ethernet. presentation to the IEEE 802.3az Task Force, Nov. 2007.

[8] A.P. Bianzino, C. Chaudet, F. Larroca, D. Rossi, and J. Rougier. Energy-aware routing: a reality check. In *GLOBECOM Workshops*, pages 1422–1427. IEEE, 2010.

[9] 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. *Communications Surveys & Tutorials*, (99):1–22.

[10] P. Monti, A. Muhammad, I. Cerutti, C. Cavdar, L. Wosinska, P. Castoldi, and A. Tzanakaki. Energy-efficient lightpath provisioning in a static wdm network with dedicated path protection. In *Transparent Optical Networks (ICTON), 2011 13th International Conference on*, pages 1–5. IEEE, 2011.

[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 *GLOBECOM 2010, Global Telecommunications Conference*, pages 1–5. IEEE.

[12] C. Cavdar, F. Buzluca, and L. Wosinska. Energy-efficient design of survivable wdm networks with shared backup. In *GLOBECOM 2010, Global Telecommunications Conference*, pages 1–5. IEEE.

[13] A. Jirattigalachote, C. Cavdar, P. Monti, L. Wosinska, and A. Tzanakaki. Dynamic provisioning strategies for energy efficient wdm networks with dedicated path protection. *Optical Switching and Networking*, 2011.

[14] N.H. Bao, L.M. Li, H.F. Yu, Z.Z. Zhang, and H.B. Luo. Power-aware provisioning strategy with shared path protection in optical wdm networks. *Optical Fiber Technology*, 2012.

[15] B. Addis, A. Capone, G. Carello, L.G. Gianoli, and B. Sansò. Energy-aware multiperiod traffic engineering with flow-based routing. *Accepted to ICC 2012, Workshop on Green Communications and Networking, 15th June*, 2012.

[16] L. Chiaraviglio, M. Mellia, and F. Neri. Minimizing isp network energy cost: Formulation and solutions. *Networking, IEEE/ACM Transactions on*, PP(99), 2011.

[17] N. Vasić and D. Kostić. Energy-aware traffic engineering. In *Proc. of the 1st International Conference on Energy-Efficient Computing and Networking*, pages 169–178. ACM, 2010.

[18] E. Amaldi, A. Capone, L.G. Gianoli, and L. Mascetti. Energy management in ip traffic engineering with shortest path routing. In *IEEE WoWMoM 2011, Sustainet Workshop*.

[19] E. Amaldi, A. Capone, L.G. Gianoli, and L. Mascetti. A milp-based heuristic for energy-aware traffic engineering with shortest path routing. *Network Optimization*, pages 464–477, 2011.

[20] A. Cianfrani, V. Eramo, M. Listanti, and M. Polverini. An ospf enhancement for energy saving in ip networks. In *Computer Communications Workshops (INFOCOM WKSHPS), 2011 IEEE Conference on*, pages 325–330. IEEE, 2011.

[21] M. Zhang, C. Yi, B. Liu, and B. Zhang. Greente: Power-aware traffic engineering. In *Network Protocols (ICNP), 18th IEEE International Conference on*, pages 21–30. IEEE, 2010.

[22] F. Cuomo, A. Abbagnale, A. Cianfrani, and M. Polverini. Keeping the connectivity and saving the energy in the internet. In *Computer Communications Workshops, INFOCOM*, pages 319–324. IEEE, 2011.

[23] A.P. Bianzino, L. Chiaraviglio, and M. Mellia. Grida: A green distributed algorithm for backbone networks. In *Proc. of GreenCom*, pages 113–119. IEEE, 2011.

[24] M. Pióro and D. Medhi. *Routing, Flow and Capacity Design in Communication and Computer Networks*. Morgan Kaufman, 2004.

[25] S. Orlowski, R. Wessäly, M. Pióro, and A. Tomaszewski. Sndlib 1.0 survivable network design library. *Networks*, 55(3):276–286, 2010.