Energy aware management of resilient networks with shared protection

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***Abstract*—This paper addresses the problem of minimizing the energy consumption of IP networks. As traffic demands vary over time, energy savings are achieved by adapting traffic routing and node and link sleeping patterns while guaranteeing QoS and survivability requirements. Network survivability is based on shared protection for single link failures. The optimization framework considers a set of time intervals and, to guarantee network stability, inter-period limitations are imposed. Both exact and heuristic methods are proposed. Results obtained with realistic networks operated with flow-based routing protocols show that i) up to 60% of the energy savings can be achieved without negatively affecting the network resiliency and that ii) the shared protection scheme better exploits backup capacity than the dedicate protection one.**

I. INTRODUCTION

The ICT sector has a significant impact on the world energy consumption, contributing 2% (0.8 Gt CO2) to the annual global greenhouse gas (GHG) emissions [1]; moreover, in 2007 the Internet was responsible for 5.5% of the total energy consumption in the world [2]. However, the network energy consumption can be reduced. In fact, although network utilization varies typically from 5% (nightly hours) to 50% (peak hours) [3], the network consumption remains practically constant because the energy consumed by network devices is almost independent of the traffic load [4]. Therefore, *Green Networking* is an increasingly important area. Green Networking aims at optimizing energy consumption of telecommunication networks by working at different levels, i.e. developing energy efficient network devices, methodologies for power aware network design and energy management strategies [5], [6].

In this paper we address the problem of limiting the energy-wise negative effects due to capacity over provisioning in IP networks, while guaranteeing the QoS and the network resilience to single link failures, based on shared protection. We assume that unused devices can be switched off (put in sleep mode). *Traffic Engineering* (TE) techniques are applied in order to adapt traffic routing so as to optimize the use of the active network infrastructure, guaranteeing at the same time the availability of the resources necessary for network resiliency (*Energy and Survivability Aware Traffic Engineering*, ESA-TE). To guarantee network survivability, additional network resources must be available 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 demands in different time periods, it is possible to achieve remarkable energy savings while guaranteeing protection to failures.

We consider the shared protection scheme, according to which both a primary and a backup path (used to transmit data only in case of failures) are chosen for each demand. A capacity is allocated on each link to deal with primary and backup paths routed on it. The capacity devoted to backup paths can be shared among different demands, provided that their primary paths are not affected by the same set of link faults (see Figure 1). Thus, on each link a capacity must be installed so as to deal with the amount of traffic of all primary paths routed on it and each subset of the backup paths, such that their primary paths are affected by at least one common fault. 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 summary, we address a multi-period optimization problem, where the energy consumption of IP networks is minimized over a set of time intervals, while guaranteeing QoS and resilience to single link failures (with shared protection). Some inter periods constraints are used to limit the number of device switching-on along the entire set of intervals, with the aim of guaranteeing network stability and extending device lifetime. Moreover, in order to ensure QoS, we consider two different maximum link utilization thresholds: one used in case of normal network operation, the other when a link failure occurs. 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 considered as negligible, assuming

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that links can be put in sleep mode and quickly reactivated only when needed, and thus only primary path related consumption is optimized. Actually, in case of link failure on the primary path, backup 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]. As faults occur rarely and normal operation is quickly recovered, backup devoted links can be considered in sleep mode for almost all the time, and therefore their consumption can be neglected.

We propose MILP formulations and a heuristic method based on the same MILP formulations 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), based on mathematical programming models, is proposed. A set of numerical results obtained on five realistic instances are shown and discussed in Section V. Finally, concluding remarks are given in Section VI.

II. Related Work

Following the seminal work of Gupta and Sigh [5], there has been an intensive interest in the area of Green Networking. We refer the reader to [6], [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, only few articles deal with the joint problem of energy-aware traffic engineering and network survivability and they exclusively treat the WDM domain [10], [11], [12], [13], [14]. They aim at efficiently optimizing the lightpaths at the optical layer so that devices that are not used or that are carrying back-up paths can be put to sleep. An ILP path formulation (based on pre-computed paths) that considers a dedicated protection scheme is proposed in [11], while some heuristic approaches for the same problem are presented in [10], [13]. The shared protection scheme considered in this paper is instead taken into account by the heuristic algorithms proposed in [12], [14]. Differently from all these work, i) we consider a multi-period scenario, ii) we work at the IP level, and iii) we propose both exact and heuristic methods. Moreover, we consider two different max-utilization thresholds that account for the two cases when a link failure has occurred or not.

The other area touched in this paper is energy-aware *TE*, which has been largely explored in recent years, but without taking into account survivability issues or multiperiod optimization, except for our previous article on energy-aware *TE* [15]. In this area, the literature can be classified according to the routing protocol accounted for. The per-flow routing considered in this paper has been previously adopted in [16], [17]. The strategy for the off-line network energy management proposed in [16] is based on a greedy algorithm that aims at switching off the unused nodes and interfaces. A single set of traffic demands is considered. Some on-line Energy-Aware Traffic Engineering (EATe) algorithms to optimize the network power consumption are instead presented in [17]; these methods are based on a local search procedure and exploit the assumption that network device consumption is strongly dependant on the utilization.

The shortest path routing is instead treated in [18], [19], [20], [21]. The strategies proposed in [18], [19] are heuristics that aim at minimizing the network energy consumption while limiting a measure of the network congestion by efficient link weight optimization. Different algorithms for link weights configuration are proposed in [22], but no congestion optimization is explicitly considered. Finally, the Energy Aware Routing (EAR) algorithm presented in [21] is based on a modified OSPF version where neighbouring routers share the shortest path tree.

To complete this review, we mention other recent contributions based on different assumptions such as methods for energy consumption minimization of networks operated with an hybrid routing scheme (MPLS plus OSPF) [23], procedures that put to sleep network links considering only network topology features (traffic demands are disregarded) [24], a distributed algorithm to determine the operating configuration of each node so as to minimize energy consumption [25].

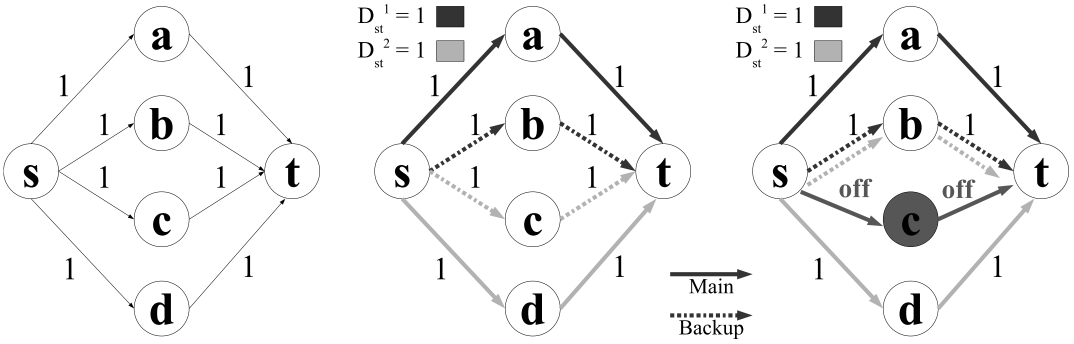
Finally, the reader is referred to [26] for a general survey on multi-period network optimization and survivable network design.

III. Problem and formulations

A. The shared protection scheme

The shared protection scheme is based on the observation that if two backup paths are never activated simultaneously, then they can share the same capacity, the needed capacity is thus reduced and, as a consequence, the energy consumption. As we consider resiliency just to single link failure, any pair of link disjoint primary paths must not be protected simultaneously. Therefore, the amount of backup capacity required is the maximum of the two traffic amounts. This scheme differs significantly from the more conservative dedicated protection scheme, where the same level of capacity is allocated to both main and backup paths and backup capacity is devoted to a single demand.

Although dedicated protection requires simpler calculations and an easier implementation, it forces the provider to reserve significant amount of capacity that will never be really exploited. In Figure 1 we show an example of how, in the context of energy-consumption optimization, shared protection can be more effective. In the 6-node network, all links have unitary capacity, and there are two



a) Network b) Dedicated Protection c) Shared Protection

Figure 1. Shared protection vs Dedicated protection.

traffic demands of unitary value (between nodes s and t) that have to be satisfied. The first demand will be routed through node a and the second one through node d. When dedicated protection is considered the back-up paths will take node b and node c, respectively, for the first and second demand. With such a scheme, enough bandwidth must be allocated to simultaneously serve both the main and the backup paths: thus all the network resources must be exploited and no element can be switched-off. As multiple link failures are not considered, and since the two main paths are disjoint, their backup paths will never be activated simultaneously. Thus, according to the shared protection scheme, we can choose the same backup path, $(s, b), (b, t)$, for the two demands, allocating one unit of capacity on both links. In this way links (s, c) and (c, t) can be switched off, as well as node c.

B. The MILP formulation

We represent the IP network with a graph $G(N, A)$. Each router is composed of a chassis and a set of line cards. Router chassis are represented by the nodes N. The set of line cards connecting router $i \in N$ and router $j \in N$ is represented by link (i, j), and an integer n_{ij} that is the number of line cards installed on that link ($n_{ij} \geq 1$). The considered daily time horizon is divided into 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 $r_d^\sigma \in [0, 1]$, for each $\sigma \in S$, which represents the fraction of the nominal value ρ_d that must be satisfied during scenario σ. The average value of the fraction r_d^σ that has to be satisfied during scenario σ follows the profile shown in Figure 2 for all $d \in D$.

We aim at minimizing the network energy consumption, by putting in sleep mode unnecessary line cards and chassis. Let parameters 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 fraction of chassis hourly energy consumption needed for a chassis switching-on. The objective function, which aims at minimizing the overall network power consumption of cards and chassis and the power consumption due to the switching-on of the chassis, can be expressed as:

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

where y_j^σ are binary variables which are equal to 1 if chassis j is on during scenario σ, w_{ij}^σ are integer variables in $\{0, \dots, n_{ij}\}$ which represent the number of active line cards on link (i, j) during scenario σ, z_j^σ are non negative continuous variables, which represent the energy consumption due to chassis j switching-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 path and one

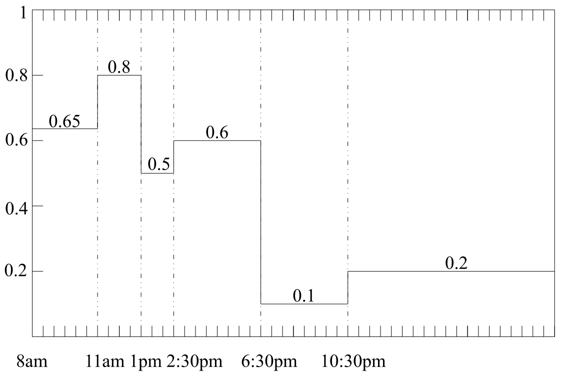


Figure 2. Traffic scenarios.

backup path. Two binary variables $x_{ij}^{d\sigma}$ and $\xi_{ij}^{d\sigma}$ are defined for each demand d, each link (i,j) and each scenario σ, such that $x_{ij}^{d\sigma}$ ($\xi_{ij}^{d\sigma}$) are equal to 1 if the primary path (backup path) of demand d is routed on link (i,j) in scenario σ, and 0 otherwise. Routing variables must satisfy the following flow conservation constraints:

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

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

where b_i^d is set to 1 if $i = o_d$, to -1 if $i = t_d$ and to 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:

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

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

The following chassis status constraints force the proper value of variables y_j^σ:

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

where ψ is the chassis capacity. The constraints state that a chassis can be switched off in a scenario only if no demand is routed through it, neither in the primary nor in the backup path.

To represent the card energy consumption due to the backup paths, a binary variable $g_{ijkl}^{d\sigma}$ is defined for each pair of links (i,j) and (k,l), each demand d and each scenario σ, such that $g_{ijkl}^{d\sigma}$ are equal to 1 if links (i,j) and (k,l) belong to the primary path and to the backup path serving the demand d in scenario σ, respectively. The following constraints force the proper value of variables $g_{ijkl}^{d\sigma}$:

$$g_{ijkl}^{d\sigma} \ge x_{ij}^{d\sigma} + \xi_{kl}^{d\sigma} - 1, \forall (i,j), (k,l) \in A, \forall d \in D, \forall \sigma \in S \quad (8)$$

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

$$\sum_{d\in D} r_d^\sigma \rho_d x_{ij}^{d\sigma} \le \mu_a \gamma w_{ij}^\sigma, \forall (i,j) \in A, \forall \sigma \in S \quad (9)$$

$$\sum_{d\in D} r_d^\sigma \rho_d \left(x_{ij}^{d\sigma} + g_{klij}^{d\sigma} \right) \le \mu_b \gamma w_{ij}^\sigma, \forall (i,j), (k,l) \in A, \forall \sigma \in S \quad (10)$$

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. Note that according to the shared protection scheme, the available capacity on each link has to be enough for coping with each possible link failures (different link failures activate different backup paths).

Moreover, we have to keep active the same number of line cards for both the directions of a link:

$$w_{ij}^\sigma = w_{ji}^\sigma, \forall \sigma \in S, \forall (i,j) \in A : i < j \quad (11)$$

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 the number of switching to a given ε :

$$\sum_{k=1}^{n_{ij}} u_{ijk}^\sigma \ge w_{ij}^\sigma - w_{ij}^{\sigma-1}, \quad \forall (i,j) \in A, \forall \sigma \in S \quad (12)$$

$$\sum_{\sigma\in S} u_{ijk}^\sigma \le \varepsilon, \qquad \forall (i,j) \in A, \forall k \quad (13)$$

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

$$x_{ij}^{d\sigma}, \xi_{ij}^{d\sigma}, y_j^\sigma, u_{ijk}^\sigma \in \{0,1\}, \quad (14)$$
$$\forall d \in D, \forall \sigma \in S, \quad \forall (i,j) \in A, \forall k \le n_{ij}$$
$$z_j^\sigma \ge 0, \qquad \forall \sigma \in S, \forall j \in N \quad (15)$$
$$w_{ij}^\sigma \in \{0, \dots, n_{ij}\}, \qquad \forall \sigma \in S, \forall (i,j) \in A \quad (16)$$

C. The no backup consumption MILP model

We also consider a second version of the problem, in which only line cards energy consumption due to primary paths is considered. Backup paths are used for a 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. To model this problem we keep the objective function (1), constraints (2), (3), (4), (5), (6), (8), (7), (11), (12), (13) and domain constraints as they are, while we modify cards status and capacity constraints. The status of cards is forced by constraints (9), while constraint (10) is replaced by

$$\sum_{d\in D} r_d^\sigma \rho_d \left(x_{ij}^{d\sigma} + g_{klij}^{d\sigma} \right) \le \mu_b \gamma n_{ij} y_j^\sigma,$$
$$\forall (i,j), (k,l) \in A, \forall \sigma \in S. \quad (17)$$

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

Constraints (17) guarantee that the capacity on each link is not exceeded by the sum of active and backup resources allocated on it, when all the cards are switched on. However, the status of cards is forced by primary paths only, as described by (9).

IV. The single period heuristic

Since very large instances cannot be efficiently solved to optimality with the two formulations we have developed a heuristic algorithm which computes 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 constraints 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 previous time intervals. Every time a new time interval is optimized, all parameters are updated according to the computed solution and they are used in a modified version of constraints (2), (12), (13). 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 remaining time intervals. Since the final solution may vary according to the starting time period, we repeat the procedure using each time interval as the starting one (the total number of single periods solved is 36), and then we take the best solution.

Table II
Comparison between the efficiency of the shared protection and the dedicated protection schemes.

Max traffic matrix sust						*Shared*	*Ded*
ID	Net	$\|N\|$-$\|N_c\|$	$\|A\|$	$\|D\|$	*equip*	ϖ	ϖ
1	pol	12-6	36	15	alfa	1053.73	941.83
2	pol	12-6	36	15	delta	408.32	364.96
3	pol	12-6	36	15	eta	2634.32	2354.57
4	pol	12-3	36	35	alfa	618.99	531.46
5	pol	12-3	36	35	delta	239.86	205.94
6	pol	12-3	36	35	eta	1547.48	1328.64
7	n-us	14-7	42	21	alfa	1964.56	1827.96
8	n-us	14-7	42	21	delta	761.26	708.33
9	n-us	14-7	42	21	eta	4911.38	4569.89
10	n-us	14-4	42	45	alfa	1280.79	1133.33
11	n-us	14-4	42	45	delta	496.31	439.17
12	n-us	14-4	42	45	eta	3201.98	2833.33
13	atl	15-8	44	42	alfa	263.00	225.81
14	atl	15-8	44	42	delta	101.91	87.50
15	atl	15-8	44	42	eta	657.52	564.53
16	n-gr	17-9	52	28	alfa	18039.28	16451.61
17	n-gr	17-9	52	28	delta	6990.48	6375.00
18	n-gr	17-9	52	28	eta	45099.94	41129.03

Table III
Comparison between the energy savings achieved by both solving the exact formulations and running ESA-STH.

MILP		B_{on}			B_{off}		
ID	Net	$\%E_c$	$\%G_o$	$tl(h)$	$\%E_c$	$\%G_o$	$tl(h)$
1	pol	66.6	3.6	4	64.6	1.9	4
2	pol	57.9	6.2	4	53.8	2.7	4
3	pol	65.9	2.9	4	63.8	1.7	4
7	n-us	62.9	13.2	6	58.0	4.7	4
8	n-us	53.1	21.5	12	46.5	7.7	4
9	n-us	61.2	11.7	6	57.4	5.0	4
ESA-STH		B_{on}			B_{off}		
ID	Net	$\%E_c$	$\%G_m$	$\tau^\sigma(m)$	$\%E_c$	$\%G_m$	$\tau^\sigma(m)$
1	pol	66.4	-0.3	6	64.3	-0.3	3
2	pol	57.0	-0.9	6	53.4	-0.4	3
3	pol	65.7	-0.2	6	64.0	0.2	3
7	n-us	60.3	-2.6	10	57.3	-0.7	3
8	n-us	51.0	-2.1	10	46.3	-0.2	3
9	n-us	59.6	-1.6	10	56.7	-0.7	3

V. Computational results

A. Network scenarios

We have tested and compared results obtained with the MILP formulation and the ESA-STH heuristic for both versions of the problem. Tests are run on four instances based on networks of the SNDLib [27]: *polska*, *nobel-us*, *atlanta*, and *nobel-germany* networks. In each network all routers are assumed to be of the same type. We considered three different cases, *alfa*, *delta*, and *eta*, which use the same chassis but different types of cards. Their capacity and consumption are provided in Table I. For each network, the nodes are divided into edge and core routers by randomly choosing the subset of core nodes, which are neither source nor destination nodes, and therefore are the only ones that can be put into sleep mode. The nominal traffic demand amounts ρ_d have been obtained scaling by

Table IV
Comparison between the energy savings achieved with the different protection schemes.

Istance			Shared		Dedicated	
			B_{on}	B_{off}	B_{on}	B_{off}
ID	Net	$\tau^\sigma(m)$	$\%E_c$	$\%E_c$	$\%E_c$	$\%E_c$
1	pol	3	66.4	64.3	71.6	68.1
2	pol	3	57.0	53.4	62.1	55.0
3	pol	3	65.7	64.0	71.0	67.3
4	pol	3	70.6	69.6	76.9	72.2
5	pol	3	62.3	59.6	68.7	60.2
6	pol	3	70.2	69.1	76.3	71.4

Table V
Computational results obtained running ESA-STH for shared protection with *nobel-us*, *atlanta* and *nobel-germany* networks.

Istance		B_{on}		B_{off}	
ID	Net	$\%E_c$	$\tau^\sigma(m)$	$\%E_c$	$\tau^\sigma(m)$
7	n-us	60.3	10	57.3	3
8	n-us	51.0	10	46.3	3
9	n-us	59.6	10	56.7	3
10	n-us	78.9	30*	75.1	3
11	n-us	67.8	30*	61.3	3
12	n-us	77.4	30*	74.3	3
13	atl	73.8	60**	71.8	5
14	atl	62.8	60**	56.1	5
15	atl	73.0	30*	69.7	5
16	n-gr	76.0	60**	72.2	5
17	n-gr	64.3	60**	57.3	5
18	n-gr	75.8	10	71.9	5

a fixed parameter ϖ the traffic matrices provided by the SNDLib; ϖ has been dimensioned so that the fraction of link capacity used by the primary paths is lower than μ_a, and the fraction of link capacity used by both primary and backup path is lower than μ_b, when nominal demands ρ_d are efficiently routed with dedicated protection. Note that, as we will show in next subsection, the implementation of the shared protection scheme would have allowed to manage a higher nominal traffic (see Table II).

We have generated three different scenarios of traffic for each network, where the r_d^σ parameters (fraction 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 2. 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 (maximum link utilization due to primary paths) equal to 50%, and μ_b (maximum link utilization due to 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. Note that in each table all the values corresponding to a given instance are averaged out over three randomly generated scenarios.

Table II and Figure 3 show a comparison between dedicated and shared protection schemes. In Table II the first two columns gives the instance ID and the network. Columns $|N|$-$|N_c|$, $|A|$, $|D|$ and *equip* represent the number of nodes and core nodes, links, traffic demands, and the device type, respectively. The reported values of ϖ are the maximal values that can be used to scale the SNDLib traffic matrix, while maintaining the feasibility with the nominal demands ($r_d^\sigma = 1$). The table shows that the shared protection scheme allows to manage greater traffic matrices, with an average increment of 10% w.r.t. the traffic managed with the dedicated protection. Therefore, although the complexity of the problem is significantly increased, shared protection scheme is worth to be implemented. For comparison purposes, during our tests we have always used the maximal ϖ parameters calculated with the dedicated protection.

In Table III and Figure 4 we present the comparison between the solutions obtained by solving the exact formulations with CPLEX with the hourly time limit reported in column $tl(h)$, and by running the ESA-STH algorithm with the minute time limit on the single period shown in column $\tau^\sigma(m)$. Note that the total resolution time of ESA-STH is bounded by $\tau^\sigma(m) \times 36$, and that this time can be reduced up to $\tau^\sigma(m) \times 6$ if the algorithm is run in parallel for each different starting period. We report the results for the basic problem (III-B) in columns B_{on} and for the variant (III-C) in columns B_{off}. For each version, we report the results obtained by the formulation (MILP) and the heuristic (ESA-STH): $\%E_c$ is the energy consumption normalized w.r.t. the consumption of the fully powered on network, G_o is the gap from the best lower bound and the upper bound provided by CPLEX and G_m represents the gap of the heuristic solution from the solution calculated by solving the MILP model.

Results on the exact solution show that if links carrying only backup paths have to be kept active (B_{on} column), significant energy savings are achieved, generally of about 60% and varying from 53.1% (instance 8) to 66.6% (instance 1). Note that we obtain higher energy savings with the *delta* technology, which is the one with the largest card consumption. Switching-off the links that carry only backup paths (B_{off} column) allows to further increase the energy savings of about 2% on average for the *polska* network (instances 1-2-3) and of about 6% for the *nobel-us* network (instances 7-8-9). Moreover, note that in this case the network resources are clearly divided: those dedicated to the allocation of the main paths, and those destined to carry exclusively the backup paths. Because of the considerable complexity introduced by the shared backup resources management, even small instances (instances 1-2-3 with *polska* network) cannot be solved at optimality within the considered time limit. Concerning the smaller instances, related to *polska* network, the gap varies from 2.9% to 6.3% in *Backup-on* case, and from 1.7% to 2.7% in *Backup-off* one. The possibility of switching-off the backup links allows to significantly reduce the gap for all the considered instances. A slight increase of instance size (instances 7-8-9 with *nobel-us* network) leads to substantial increasing of the gap, which rises up to 21.5% in instance 8 with active backup links. 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 smaller.

The comparison between the energy savings achieved by the formulations and by ESA-STH shows the validity and

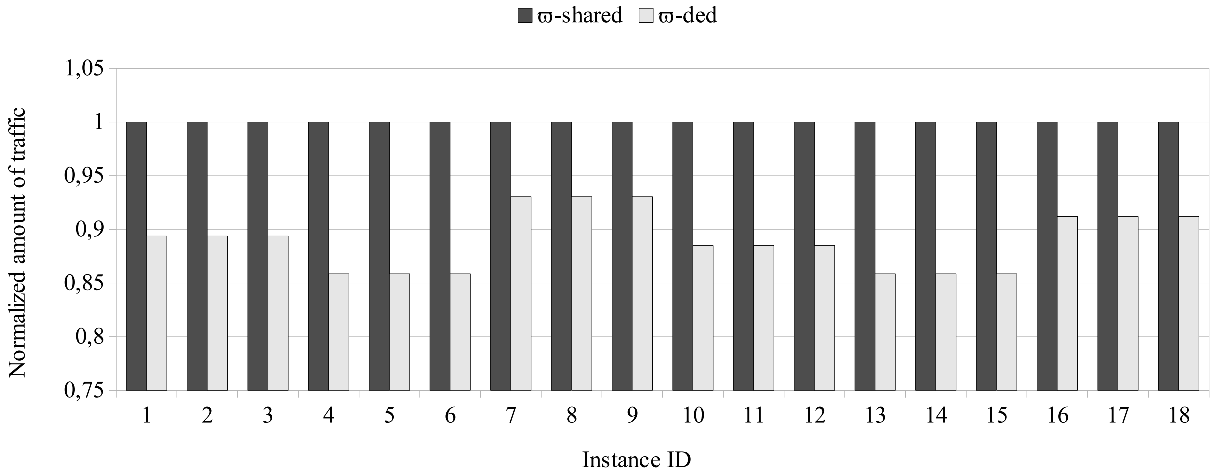


Figure 3. Comparison between the maximum amount of traffic supported by the networks with shared and dedicated protection.

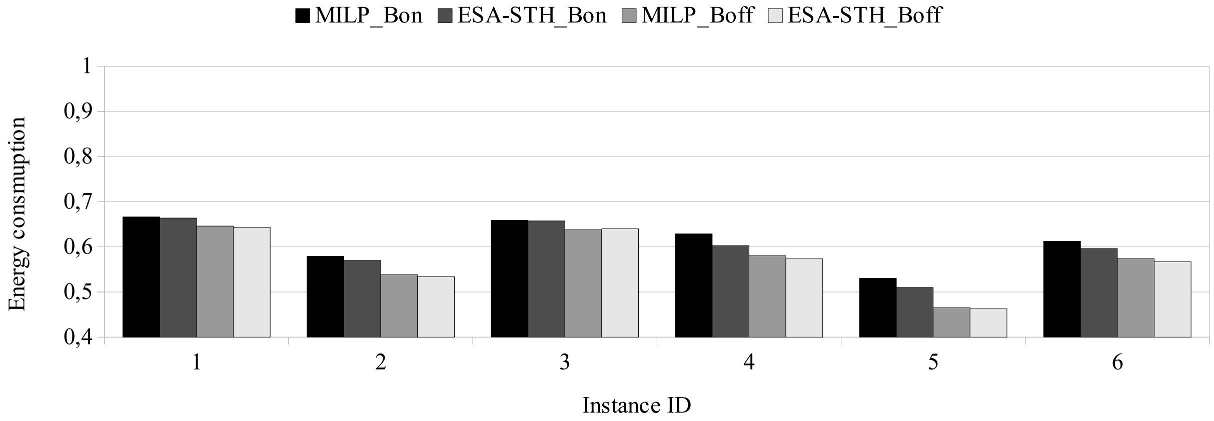


Figure 4. Comparison between the energy consumption achieved solving the MILP formulation and running ESA-STH for the two cases with backup link kept on (B_{on}) and off (B_{off}).

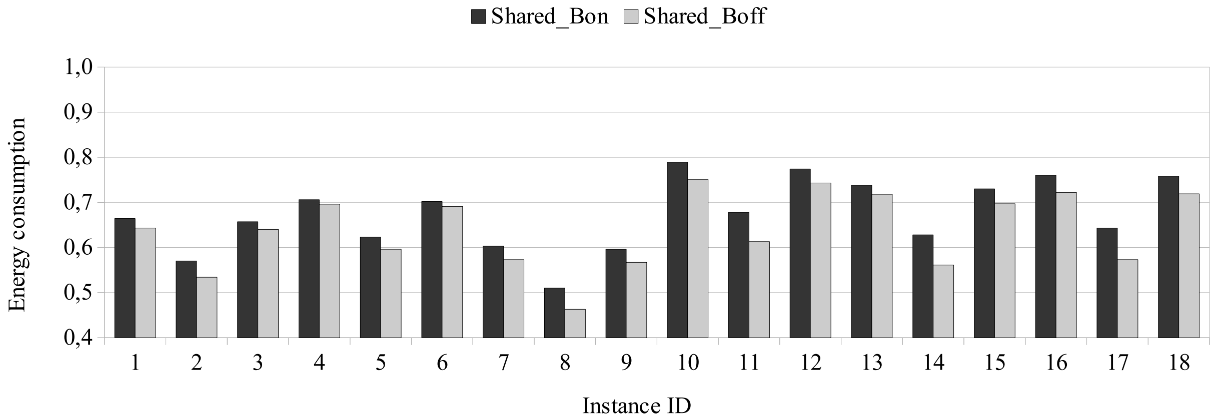


Figure 5. Energy consumption obtained running ESA-STH with shared protection for the two cases with backup link kept on (B_{on}) and off (B_{off}).

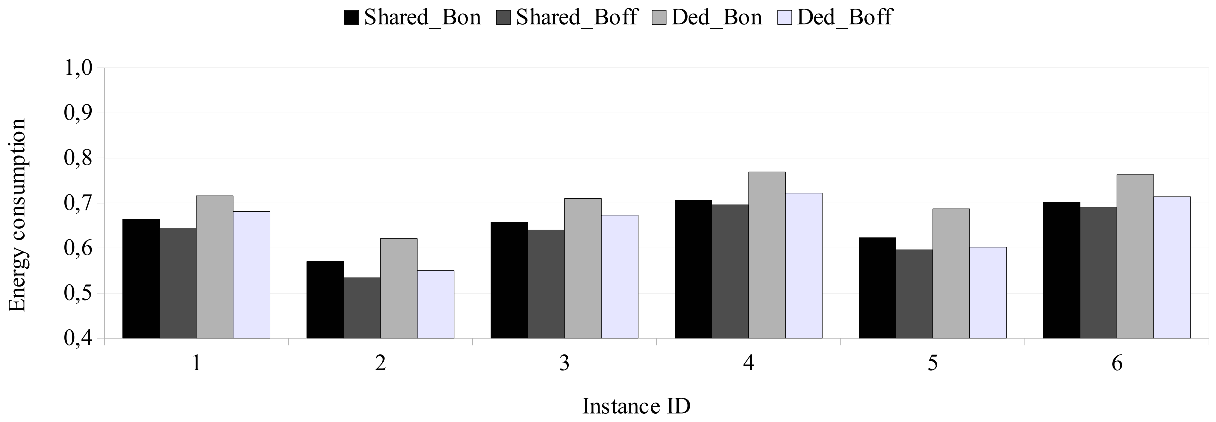


Figure 6. Energy consumption obtained running ESA-STH with both shared and dedicated protection.

efficiency of the single time period algorithm. The solution computed by ESA-STH improve upon those computed by CPLEX, providing an average increase of the energy savings of around 2% w.r.t. to those obtained by solving the formulations with the reported time limit. The gap w.r.t. the solution computed by CPLEX, shown in $\%G_m$ column, is negative in almost all the instances.

In Table IV and Figure 6, we compare the energy savings obtained running ESA-STH with shared and dedicated protection schemes. The energy consumption, normalized w.r.t. the consumption of the fully active network, is reported. The dedicated protection scheme has been discussed in our previous paper [28]. In order to model the dedicated protection it is necessary to remove constraints (8), to replace constraints (10) with

$$\sum_{d \in D} r_d^{\sigma} \rho_d \left(x_{ij}^{d\sigma} + \xi_{ij}^{d\sigma} \right) \le \mu_b \gamma w_{ij}^{\sigma}, \forall (i,j) \in A, \forall \sigma \in S \quad (18)$$

and to replace (17) with

$$\sum_{d \in D} r_d^{\sigma} \rho_d \left(x_{ij}^{d\sigma} + \xi_{ij}^{d\sigma} \right) \le \mu_b \gamma n_{ij} y_j^{\sigma}, \forall (i,j) \in A, \forall \sigma \in S. \quad (19)$$

The management of the shared resources considerably increases the problem complexity, but, as shown in Table IV and Figure 6, allows to achieve substantially larger energy savings. In fact, the energy savings obtained with the shared protection improve of about 6% when backup links are on, and of about 3% when they can be switched off, w.r.t. the savings obtained by the dedicated protection. Note that energy savings decrease when fewer core routers are available (instances 4-5-6) and thus fewer chassis can be switched-off. This is not surprising as chassis consume much more power than cards. Note that for this entire set of experiments we use the same single period time limit τ^{σ} (three minutes).

The heuristic based on the disjoint management of the single time periods manages to deal with instance dimensions up to 20 nodes and 50 traffic demands. Results on such instances are reported in Table V and Figure 5, where the normalized energy consumption, and the time limit for each time interval $\tau^{\sigma}(m)$ are reported for each case. As shown in Table V, we obtain energy savings very similar to the ones obtained with the smaller networks (*polska* and *nobel-us*) also when handling the larger instances (*atlanta* and *nobel-germany* networks). Normalized energy consumption is about 65% and 60% for the two cases when backup devoted links can or cannot be put to sleep, respectively. Moreover, this latter case seems to be much more complex, since it requires an higher time-limit (up to 60 minutes) on the solution of the single period formulation in order to find acceptable good solutions. Moreover, all the observations previously reported remain still valid with the larger networks. Note that the single * and the double ** asterisks reported near the $\tau^{\sigma}(m)$ parameter of some instances mean that ESA-STH has been performed by considering, respectively, only two different starting periods (total of 12 single periods solved) and only one single starting period (total of 6 single periods solved).

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 exploiting daily traffic variations, while guaranteeing the survivability with a shared protection scheme. We proposed MILP formulations for two different versions of the problem (where links carrying exclusively backup paths can or cannot be put into sleep mode), and a heuristic method called ESA-STH that finds solutions very close to the optimum with networks of up to 20 nodes. We achieve considerable energy savings in both cases, up to 45% when half of routers are core routers. 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.

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