Energy-Aware Multiperiod Traffic Engineering with Flow-based Routing

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***Abstract*—We propose a multi-period model to minimize the energy consumption of IP networks while guaranteeing the satisfaction of all the traffic demands. Energy savings are achieved by putting into sleep mode cards and chassis. The multi-period optimization is constrained by inter-period limitations necessary to guarantee the stability of the networks. Both exact and heuristic solutions are proposed. Results show that up to 50% of the energy savings can be achieved for realistic test scenarios in networks operated with flow-based routing protocols (i.e. MPLS).**

I. Introduction

The Internet rapid expansion has produced an increment of energy consumption and greenhouse gas emissions: it is said that the ICT sector contribution is 2% (0.8 Gt CO2) of annual global greenhouse gas (GHG) emissions [1], [2], and that in 2007 the Internet was responsible for 5.5% of the total energy consumption in the world [3]. The answer has been "green networking", that is development of i) new energy efficient network devices, ii) new methodologies for power aware network design and iii) new energy management strategies [4]. In [5] and [6], different types of Green Networking proposals are discussed and different taxonomies for green networking research are explored.

The particular focus of this paper is IP networks energy-aware management. The idea being to limit the energy-wise negative effects of bandwidth over provisioning. In fact, although network utilization varies typically from 5% (night hours) to 50% (peak hours) [7], the network consumption remains practically constant because the energy consumed by network devices is almost independent of the traffic load [8].

To induce the dependence between load and consumption, a strategy able to better exploit the network infrastructure, guaranteeing the QoS requested without wasting energy, must be devised. A promising strategy is energy-aware *Traffic Engineering* (TE) that will be carried out assuming that devices can be put to sleep.

Efficient *Traffic Engineering* maximally exploits the active capacity, maximizing in this way the energy savings. The efficiency of TE is however influenced by the routing protocol. Multi Protocol Label Switching (MPLS) is, together with the Open Shortest Path First (OSPF) protocol, the most popular protocol adopted in the backbone networks. MPLS guarantees a very flexible TE because it allows to explicitly select the route of each individual traffic demand. However, the management of a considerable number of demands can become computationally expensive (dedicated routing of each single demand), and switching a flow from one path to another requires time and overhead. Therefore, an energy management mechanism should, in general, avoid rerouting flows too often to follow traffic variations.

The problem that we address in this paper is how to optimize the energy management mechanism alongside the traffic engineering. For this purpose, we propose a multi-period optimization problem where we aim at minimizing the energy consumption of IP networks over a set of time intervals, while guaranteeing the satisfaction of all the traffic demands. A per-flow single path routing is proposed, energy savings are achieved by putting to sleep unused routers and links. Some inter periods constraints are used to guarantee network stability. An ILP formulation and a heuristic method are presented 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 modelling assumptions and the ILP formulation. In Section IV a new heuristic based on mathematical programming is proposed. A set of numerical results obtained on two real networks are shown and discussed in Section V. Finally, concluding remarks are exposed in Section VI.

II. Related Work

Despite the recent popularity of green networking studies (see [9] and [10]), to the best of our knowledge, very few articles have dealt with TE and network design issues. Part of the literature is focused on energy-aware routing and, concerning network design, some researchers have proposed a design based on the consumption profile of different routers [8], while others propose exploiting dynamic topology changes [11].

In energy-aware traffic engineering, it is useful to differentiate the proposals according to the considered routing scheme (shortest path, flow-based, hybrid, etc.).

Related to shortest path routing, in [12] and [13] efficient heuristics to optimize network energy consumption (by

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switching off both links and nodes) and network congestion, by efficiently configuring the link weights, are presented. Also the method proposed in [14] operates on link weights, but no congestion optimization is considered and only the links can be switched off. Finally the Energy Aware Routing (EAR) algorithm presented in [15] is able to switch off network elements exploiting a modified version of the OSPF protocol where only a subset of routers can compute the shortest path trees; in this case, no link weights optimization is performed and neither traffic load nor network capacity are explicitly considered.

Concerning per-flow routing, in [16] some heuristics are proposed that, given a traffic matrix and a fully powered network, are able to switch off nodes and links while respecting traffic constraints. On-line Energy-Aware Traffic Engineering (EATe) techniques to optimize link and router power consumption are instead proposed in [17] (rate-dependant energy profiles are considered).

Finally, in [18] a hybrid routing scheme is considered, where both shortest path and per-flow routing are performed, the method aims at switching off the network links while guaranteeing QoS constraints (maximum utilization and maximum path length constraints). The approach is based on an MIP formulation where the traffic demands are routed through a set of previously calculated k-shortest path.

To the best of our knowledge, no work concerning a multi-period energy-aware optimization of IP networks have been presented, which is the contribution of this paper.

III. The problem and the ILP formulation

In our problem we consider i) an IP network topology $G(N, A)$ where N is the set of routers and A is the set of links, ii) a set of traffic demands D characterized by an origin o_d and a destination t_d, and iii) a set S of time intervals σ of duration h_σ, the sum of which corresponds to an entire day. Moreover let each router $i \in N$ be composed of a chassis and a set of line cards, with n_{ij} line cards installed for link (i, j) $(n_{ij} \geq 1)$. The target of our optimization is the minimization of the network energy consumption, that can be achieved by putting in sleep mode unnecessary line cards and chassis. The objective function can be expressed as:

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

where 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, y_j^σ are binary variables that are equal to 1 when chassis j is on during scenario σ, z_j^σ are non negative continuous variables, which represent the energy cost paid if chassis j is switched on passing from scenario σ to scenario $\sigma + 1$ and finally π_{ij} and $\bar{\pi}$ are parameters representing, respectively, the power consumption of a single card connecting routers i and j, and the power consumption of a chassis.

Each traffic demand must be routed along a single path (MPLS routing). This is given by the following flow conservation constraints:

$$\sum_{(i,j) \in A} x_{ij}^{d\sigma} - \sum_{(j,i) \in A} x_{ji}^{d\sigma} = \begin{cases} 1 & \text{if } i = o_d, \\ -1 & \text{if } i = t_d, \\ 0 & \text{otherwise} \end{cases} \qquad \forall i \in N, \forall d \in D, \forall \sigma \in S \tag{2}$$

where $x_{ij}^{d\sigma}$ are binary variables that are equal to 1 when the traffic demand d is routed through arc (i, j). Note that the routing of each demand can be varied along the different time intervals.

All the traffic demands $d \in D$ have to be satisfied in all the time intervals $\sigma \in S$. Each demand d is characterized by a nominal value ρ_d, and by a real non negative parameter $r_{d\sigma} \in [0, 1]$ that indicates the amount of the nominal value ρ_d that has to be satisfied during scenario σ. The mean values of the traffic demands along the set of scenarios follow the profile shown in Figure 1. Note that, in normal conditions, traffic profiles can be predicted with good accuracy and allow planning network resources allocation in advance with limited uncertainty margins [19].

There are also capacity constraints (both for chassis and line cards):

$$\sum_{(i,j) \in A} \sum_{d \in D} r_{d\sigma} \rho_d x_{ij}^{d\sigma} + \sum_{(j,i) \in A} \sum_{d \in D} r_{d\sigma} \rho_d x_{ji}^{d\sigma} \leq \Gamma y_j^\sigma, \quad \forall j \in N, \forall \sigma \in S \tag{3}$$

$$\sum_{d \in D} r_{d\sigma} \rho_d x_{ij}^{d\sigma} \leq \mu \gamma w_{ij}^\sigma, \forall (i, j) \in A, \forall \sigma \in S \tag{4}$$

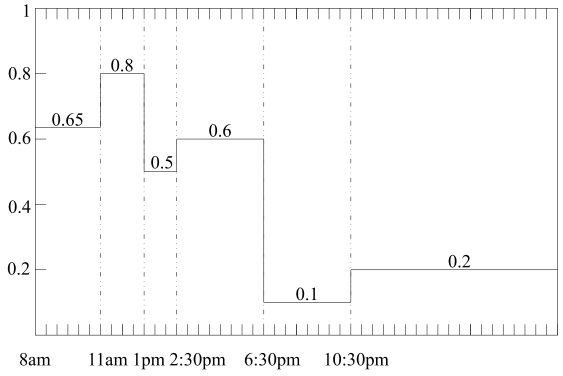

Figure 1. Traffic scenarios: Average fraction m_r of the nominal value in the different time intervals $\sigma \in S$. $r_{d\sigma}$ parameters are randomly generated with a uniform distribution in $[m_r - 0.2, m_r + 0.2]$.

the parameter μ is the allowed link capacity utilization. The power consumed by switching on a chassis is computed through the following constraints:

$$z_{j\sigma} \geq \delta\bar{\pi}\left(y_j^\sigma - y_j^{\sigma-1}\right), \forall j \in N, \forall \sigma \in S \tag{5}$$

We have to switch on the same number of line cards for both the direction of a link

$$w_{ij}^\sigma = w_{ji}^\sigma, \forall \sigma \in S, \forall (i,j) \in A : i < j \tag{6}$$

Since, for reasons of 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 life), we added the following constraints to limit to a given ε the maximum number of switching on:

$$\sum_{k=1}^{n_{ij}} u_{ijk}^\sigma \geq w_{ij}^\sigma - w_{ij}^{\sigma-1},\ \forall (i,j) \in A, \forall \sigma \in S \tag{7}$$

$$\sum_{\sigma \in S} u_{ijk}^\sigma \leq \varepsilon,\ \forall (i,j) \in A, \forall k \tag{8}$$

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:

$$x_{ij}^{d\sigma} \in \{0,1\}, \forall d \in D, \forall \sigma \in S, \forall (i,j) \in A \tag{9}$$

$$y_j^\sigma \in \{0,1\}, \forall \sigma \in S, \forall j \in N \tag{10}$$

$$z_j^\sigma \geq 0, \forall \sigma \in S, \forall j \in N \tag{11}$$

$$w_{ij}^\sigma \in \{0,\ldots,n_{ij}\}, \forall \sigma \in S, \forall (i,j) \in A \tag{12}$$

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

The ILP formulation expressed by (1)-(13) can be quickly solved at optimality with commercial solvers for instances of dimensions up to 15 nodes but not so for larger instances. For this reason, we have developed a heuristic algorithm called *Energy Aware Lexicographic GRASP* (EA-LG) that we detail in the next Section.

IV. Heuristic Methods

EA-LG is able to efficiently solve instances of up to 50 nodes and 600 traffic demands. It is based on a greedy procedure embedded into a *Greedy Randomized Adaptive Search Procedure* (GRASP) (see e.g. [20]). According to GRASP the greedy algorithm is repeated for a given number it_{max} of iterations (multi-start), modifying at each iteration the order of the elements considered. The basic greedy procedure is composed of three stages. In the first stage the traffic demands are sorted in a decreasing order. At this point each single traffic demand d is processed by performing for i_{greedy} times ($i_{greedy} = |D|$) a loop composed of the two remaining stages, the *Min-Energy* stage and the *Min-Congestion* stage. The *Min-Energy* stage aims at minimizing the energy consumption E_c^{MIN-EN} and solves (1)-(13) considering only the single demand $\bar{d}$ at the top of the sorted list. The *Min-Congestion* stage aims instead at minimizing the network congestion while maintaining the energy consumption equal to the E_c^{MIN-EN} value computed by the *Min-Energy* stage; this is done by solving a modified version of (1)-(13) where

i) the objective function minimizes a convex piecewise cost function $\phi(v_{ij})$ related to the link utilization v_{ij} (see [21]):

$$\min \quad \Phi = \sum_{(i,j)\in A} \phi(v_{ij}) \tag{14}$$

ii) the energy consumption is fixed to E_c^{MIN-EN}:

$$\sum_{\sigma \in S}\left(\sum_{j\in N} \bar{\pi} y_j^\sigma\right) h_\sigma + \sum_{\sigma\in S}\left(\sum_{(i,j)\in A} \pi_{ij} w_{ij}^\sigma\right) h_\sigma + \\ + \sum_{\sigma \in S}\sum_{j\in N} z_{j\sigma} = E_c^{MIN-EN} \tag{15}$$

iii) the cost function is expressed by:

$$\phi\left(v_{ij}^\sigma\right) \ \geq\ \alpha_q\left(b_{ij}^\sigma + \rho_{\bar{d}} x_{ij}^{\bar{d}\sigma}\right) + \\ + \beta_q \gamma w_{ij}^s, \forall (i,j) \in\ A,\ \forall \sigma \in S, \forall q\ \in\ Q \tag{16}$$

where Q is the set of the linear segments that shape the cost function $\phi(v_{ij})$. It is very important to note that in (16) we use the parameter b_{ij}^σ to keep records of the capacity necessary to route the traffic demands already processed by the algorithm. Parameters b_{ij}^σ are updated at the end of the *Min-Congestion* stage:

$$b_{ij}^\sigma = b_{ij}^\sigma + \rho_{\bar{d}} r_{\bar{d}\sigma} x_{ij}^{\bar{d}\sigma}, \forall (i,j) \in A, \forall \sigma \in S \tag{17}$$

In both the formulations used by the *Min-Energy* stage and the *Min-Congestion* stage, the card and chassis capacity constraints, (3) and (4) are also modified in order to consider the parameter b_{ij}^σ

$$\sum_{(i,j)\in A}\left(r_{\bar{d}\sigma}\rho_{\bar{d}} x_{ij}^{\bar{d}\sigma} + b_{ij}^\sigma\right) + \\ + \sum_{(j,i)\in A}\left(r_{\bar{d}\sigma}\rho_{\bar{d}} x_{ji}^{\bar{d}\sigma} + b_{ji}^\sigma\right) \leq \Gamma y_j^\sigma, \forall j \in N, \forall \sigma \in S \tag{18}$$

$$r_{\bar{d}\sigma}\rho_{\bar{d}} x_{ij}^{\bar{d}\sigma} + b_{ij}^\sigma \leq \mu\gamma w_{ij}^\sigma, \forall (i,j) \in A, \forall \sigma \in S \tag{19}$$

The *Min-Congestion* stage is the most time consuming, but it plays a fundamental role because it drastically reduces the possibility of premature stop of the greedy procedure due to saturation of device capacity. In fact, it pushes the procedure to efficiently exploit resources, so as to avoid the situation wherein no more bandwidth is available to satisfy the remaining demands. According to GRASP, at each greedy repetition the demands order is perturbed by using a technique commonly known in the literature as *Restricted Candidate List* (RCL). With RCL

Table II
Overview of different network configurations

case	device	capacity	hourly cons.
–	Chassis Juniper M10i	16Gbps	86.4 W
alpha	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

the choice of the traffic demand to process is done by randomly selecting one of the firsts $l\%$ elements of the decreasing ordered list. RCL, if combined as in our case with the multi-start, allows a better exploration of the solution space.

V. Computational Results

A. The testbed

We have tested and compared the MIP formulation (1)-(13) and EA-LG using three networks provided by the SNDLib [22], the *france network*, the *nobel-eu network* and the *germany network*.

The network nodes are divided into core and edge routers and for each network a subset of core routers was assumed; note that core routers are the only ones that can be put to sleep, since they are neither source nor destination nodes. The column N_{core} in Tables I and III, shows the number of core routers for each given test. Concerning the traffic matrices, the nominal traffic demands ρ_d have been obtained by scaling for 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. Finally, we have generated three different scenarios of traffic for each network, where the $r_{d\sigma}$ parameters (amount of the nominal value ρ_d that has to be satisfied during scenario σ) are randomly selected with a uniform distribution, centered in each scenario σ around the mean values illustrated in Figure 1. Note that in Table I we report the average values obtained for each instance using the three random traffic scenarios.

B. The results

The tests have been carried out on Intel i7 processors with 4 core and multi-thread 8x, equipped with 8Gb of RAM. All the computational results are reported in Tables I and III. where $|N|$, $|N_{core}|$, $|A|$, $|Cards|$, $|D|$ and *equip* represent, respectively, the number of nodes, core nodes, links, line cards, traffic demands and network configuration (see Table II). In the following group, E_c is the energy consumption level of the optimized network (compared with the consumption of the fully powered on network), Gap_{opt} the gap achieved by CPLEX from the best lower bound calculated and $t(min)$ the computational times in minutes. In the last group, two new parameters are introduced, Gap_{model} that represents the gap of the heuristic solution from the solution calculated by CPLEX and t_{nor} that is the resolution time ratio between the model and the heuristic. When solving (1)-(13), CPLEX has been stopped after 6 hours of elaboration, and the $t(min)$ reports the sum of the computation time of each utilized thread. Note that the parameters it_{max} (multi-start iterations) and l (percentage of demands of the RCL) of EA-LG have been respectively set to 50 and 5. For this set of tests we have considered a single line card available on each link ($n_{ij} = 1 \forall (i,j) \in A$) with a maximum utilization allowed of 50% ($\mu = 0.5$).

>From Table I, the first observation is that both, the model and EA-LG, decrease the energy consumption up to 55% and generally around 60% (if compared with the consumption of the full active network). The optimized energy consumption varies instead from 82% to a maximum of 94% when we have only edge routers and thus only line cards can be switched-off (Tests 3-6-9-12-15-18). These results were expected because chassis are the more power consuming devices (see Table II) and therefore they need to be switched off to achieve substantial savings. Concerning the methodological performance, it can be observed that the model gets a gap from the bound around 3% when working with the *france network* (tests from 1 to 9), and around 5% when working with the slightly bigger *nobel-eu network* (tests from 10 to 18). This result is quite good but the resolution time needed to achieve it was around 40 hours. EA-LG solutions are instead slightly worse than those computed solving the model (maximum gap from model solution of 5.81% with *france network* in test 4, and of 2.89% with *nobel-eu network* in test 10), but resolution times are up to 150 times faster (see column t_{nor}), and generally around 30 minutes (with $it_{max} = 50$) with a maximum of 67 minutes in test 9. Moreover, it is important to note that a slight increase of the network dimensions (*nobel-eu network* has 3 more nodes and 70 more traffic demands) greatly reduces the performance gap between the two methods and, in tests 14 and 17, EA-LG achieves even better results (negative gap from the model). Also note that concerns the gap between the model and EA-LG is generally greater for the instances with fewer edge nodes (Tests 1-4-7-10-13-16). Finally, since line cards utilization is always maintained under 50%, network performance is not negatively influenced by the energy saving procedure.

As shown in Table III, EA-LG is also able to achieve the same levels of energy savings when operating the substantially bigger *germany network* (Tests 19-20-21-22-23-24). Computational times did not increase because we experimented with a smaller number of GRASP iterations ($it_{max} = 20$).

VI. Conclusion

A new energy-aware traffic engineering multi-period problem with inter-periods constraints was addressed in this paper. The aim was minimizing the energy consumption of an IP network for an entire day, while guaranteeing the satisfaction of all the traffic demands. For this, we proposed an ILP formulation and a heuristic algorithm called EA-LG that finds solutions very close to the optimum with

Table I
COMPUTATIONAL RESULTS FOR FRANCE AND NOBEL-EU NETWORKS.

france network							**(1)-(13)**			**EA-LG**			
$Test$	$\|N\|$	$\|N_{core}\|$	$\|A\|$	$\|Cards\|$	$\|D\|$	$Equip$	E_c	Gap_{opt}	$t(min)$	E_c	Gap_{model}	$t(min)$	t_{nor}
1	25	12	90	90	78	alfa	59.8%	2.16%	2780.4	62.2%	4.08%	18.3	151.9
2	25	7	90	90	153	alfa	75.2%	1.87%	2623.0	76.4%	1.59%	24.6	106.6
3	25	0	90	90	300	alfa	91.2%	3.00%	1678.9	91.7%	0.52%	32.6	51.6
4	25	12	90	90	78	delta	53.8%	2.71%	2787.5	56.9%	5.81%	21.3	131.1
5	25	7	90	90	153	delta	67.9%	4.48%	2575.2	70.9%	4.39%	18.6	138.6
6	25	0	90	90	300	delta	82.3%	6.29%	1887.5	83.5%	1.47%	58.2	32.4
7	25	12	90	90	78	eta	59.5%	1.88%	2781.2	62.1%	4.32%	18.6	149.1
8	25	7	90	90	153	eta	74.7%	2.16%	2611.7	75.7%	1.31%	17.0	153.8
9	25	0	90	90	300	eta	90.6%	2.98%	1805.2	91.1%	0.59%	67.4	26.8
nobel-eu network							**(1)-(13)**			**EA-LG**			
$Test$	$\|N\|$	$\|N_{core}\|$	$\|A\|$	$\|Cards\|$	$\|D\|$	$Equip$	E_c	Gap_{opt}	$t(min)$	E_c	Gap_{model}	$t(min)$	t_{nor}
10	28	14	82	82	91	alfa	65.9%	3.44%	2642.0	67.8%	2.89%	26.5	99.8
11	28	7	82	82	210	alfa	73.9%	2.04%	2301.9	74.0%	0.14%	34.4	66.8
12	28	0	82	82	377	alfa	94.1%	3.95%	2040.0	94.2%	0.11%	45.2	45.1
13	28	14	82	82	91	delta	61.6%	5.19%	2611.8	63.3%	2.73%	32.1	81.5
14	28	7	82	82	210	delta	69.2%	5.42%	2311.8	69.2%	-0.08%	27.3	84.7
15	28	0	82	82	377	delta	87.7%	8.86%	2000.8	88.0%	0.37%	47.7	42.0
16	28	14	82	82	91	eta	65.7%	3.48%	2627.9	67.4%	2.55%	25.2	104.3
17	28	7	82	82	210	eta	73.8%	2.51%	2277.4	73.7%	-0.08%	26.0	87.5
18	28	0	82	82	377	eta	93.7%	4.22%	2057.0	93.8%	0.12%	46.4	44.3

networks of up to 28 nodes. Given the efficiency of the EA-LG, it can be naturally used to solve much larger instances. We have been able to save up 45% of energy in the cases when 50% of routers are core routers. We are currently working on the development of new features to speed up both the model and EA-LG and on the addition of new inter-periods constraints.

Table III
COMPUTATIONAL RESULTS FOR GERMANY NETWORK.

germany network							**EA-LG**	
$Test$	$\|N\|$	$\|N_{core}\|$	$\|A\|$	$\|Cards\|$	$\|D\|$	$Equip$	E_c	$t(min)$
19	50	25	176	176	182	alfa	66.8%	29.8
20	50	12	176	176	397	alfa	79.0%	26.8
21	50	25	176	176	182	delta	61.8%	47.5
22	50	12	176	176	397	delta	73.0%	24.9
23	50	25	176	176	182	eta	66.0%	26.3
24	50	12	176	176	397	eta	79.0%	46.2

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