Minimization of Energy Consumption in IP/SDN Hybrid Networks using Genetic Algorithms

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***Abstract*—Although most of the efforts to tackle the energy consumption problem on wired communication networks have been made on traditional IP networks, energy-aware protocols require of several coordination tasks that are not easy to implement on current networking equipment. By exploiting the flexibility and programmability provided by the emerging Software-Defined Networking (SDN) paradigm, this paper investigates the problem of saving energy in hybrid IP/SDN networks where traditional IP nodes are incrementally replaced by SDN ones. To solve it, a Genetic Algorithm is proposed and evaluated through simulations over realistic network topologies. Results show that a reduced percentage such as 60% of SDN nodes would be enough to achieve significant reductions in energy consumption during the transition from IP to SDN, with a performance gap less than 7.5% compared to fully-deployed SDN networks.**

***Index Terms*—Energy efficiency, hybrid network, partially-deployed SDN, Genetic Algorithm.**

I. Introduction

Huge efforts to reduce the energy consumption in wired communication networks have been done by the research community in recent years. Considering the idea of powering off as many network elements (i.e. nodes and/or links) as possible while satisfying traffic requests and QoS (Quality of Service) constraints, both optimal and heuristic solutions have been proposed in the green networking area [1].

The irruption of the Software-Defined Networking (SDN) paradigm has also attracted the attention of the research community to let SDN networks be energy efficient [2]. The separation of data and control planes and the existence of a logically centralized device (namely controller) which has a global network view and is able to coordinate all the control decisions, give the opportunity of proposing new algorithms to exploit these features and therefore reduce the energy consumption [3].

However, the inclusion of this new paradigm in already deployed networks (e.g. Internet Service Provider networks) seems to be difficult, at least, in the short term. Budget limitations and the fact of being a novel paradigm motivate network operators to upgrade existing networks step by step, changing some of the network elements and evaluating their practicality after a particular time period [4].

A hybrid IP/SDN network is therefore composed of a set of legacy IP nodes and a set of SDN nodes connected by a set of links. In this scenario, the controller is able to manage the set of SDN nodes and apply a predefined control logic to solve different kind of optimization problems, such as traffic engineering [5] or green networking [6].

To the best of our knowledge, the closest work to the one described in this paper is [7], where the authors propose to extend the OpenFlow protocol to integrate the energy-aware capabilities offered by the Green Abstraction Layer (GAL) [8]. Simulations were carried out on both full and hybrid scenarios, where SDN nodes have energy-efficient capabilities and hardware components of legacy IP nodes are always fully powered. Results show the effectiveness of OpenFlow-GAL integration, by minimizing the network-level energy consumption while respecting performance constraints in traffic handling.

Different from [7], this paper focuses on providing a practical answer to the percentage of traditional IP nodes that must be upgraded to SDN to achieve significant power saving gains during the transition from IP to SDN networks. Since this optimization problem is known to belong to the NP-hard problem class [9], a Genetic Algorithm (GA) is proposed to solve it on large networks. GAs are a well established method for optimizing network topologies and have been widely used to solve the routing problem in the networking context [10]. Through simulations over realistic and different sized network topologies, we obtain the power saving percentage after varying the number of SDN nodes and the method to select the nodes to be replaced. In this way, significant power savings would be achieved without the need of replacing the network elements all at once, but progressively in stages.

The rest of the paper is organized as follows. Section II defines and formalizes the problem this work aims to solve. Based on this formulation, a GA is proposed in Section III to be applied over networks with different sizes. Experimental results are provided in Section IV whilst some conclusion remarks are given in Section V.

II. Problem Definition

In the hybrid IP/SDN scenario, let us consider a network graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$, with a set of $n \in \mathcal{N}$ nodes connected by a set of $l \in \mathcal{L}$ unidirectional links. Let us also consider two different subset of nodes: $\mathcal{N}_\mathcal{S} \subseteq \mathcal{N}$ as the set of SDN nodes and $\mathcal{N}_\mathcal{I} \subseteq \mathcal{N}$ as the set of legacy IP nodes. Regarding the set of links, let $\mathcal{L}_\mathcal{S} \subseteq \mathcal{L}$ and $\mathcal{L}_\mathcal{I} \subseteq \mathcal{L}$ be the set of unidirectional links connected to SDN nodes ($\mathcal{N}_\mathcal{S}$), and IP nodes ($\mathcal{N}_\mathcal{I}$), respectively. If a link $l \in \mathcal{L}$ is connected to a SDN node $n^S \in \mathcal{N}_\mathcal{S}$, it turns into $l^S \in \mathcal{L}_\mathcal{S}$. On the contrary,

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if both ends of the link are traditional IP nodes, it becomes $l^I \in \mathcal{L_I}$. In both cases, each link $l \in \mathcal{L}$ has a C_l capacity and an associated W_l power consumption.

Traffic description is given by a traffic matrix $\mathcal{T}_t$ comprising a set of demands $(s,d) \in \mathcal{T}_t$ which are sent from each source $n \in \mathcal{N}$ to each destination $d \in \mathcal{N}$ in the network during a particular time interval, t. Finally, $\mathcal{D} = (\mathcal{T}_t)$ represents the set of traffic matrices that all together provide complete coverage for the daily cycle. In order to describe the problem formulation by means of Integer Linear Programming (ILP), two different variables must be previously explained:

- x_{l^S} is a binary decision variable which represents the state of link $l^S \in \mathcal{L_S}$. If the link is powered on, then $x_{l^S} = 1$. Otherwise, $x_{l^S} = 0$ if it is put to sleep.
- $f_l^{s,d}$ is a binary flow variable which indicates if the demand $(s,d) \in \mathcal{T}_t$ is routed over link $l \in \mathcal{L}$. In that case, $f_l^{s,d} = 1$. Otherwise, $f_l^{s,d} = 0$.

In our model, it is assumed that only the links managed by the SDN controller (i.e. the ones connecting at least one SDN node) are able to be put to sleep and wake up when necessary. Therefore, a powered on link $l^S \in \mathcal{L_S}$ has an associated W_{l^S} power consumption, otherwise its consumption is considered to be 0. On the contrary, those links which are not under control, $l^I \in \mathcal{L_I}$, are considered to be always powered on and, therefore, they operate at their full rate. Using the previous notation, problem formulation is described by $(1-5)$:

$$min \sum_{l^S \in \mathcal{L_S}} x_{l^S} W_{l^S} + \sum_{l^I \in \mathcal{L_I}} W_{l^I} \tag{1}$$

subject to

$$\sum_{j \in \mathcal{N}_i^-} f_{l_{i,j}}^{s,d} - \sum_{j \in \mathcal{N}_i^+} f_{l_{j,i}}^{s,d} = \begin{cases} 1 & \text{if } i = s \\ -1 & \text{if } i = d \quad \forall i \in \mathcal{N}, (s,d) \in \mathcal{T}_t \\ 0 & \text{if } i \neq s,d \end{cases} \tag{2}$$

$$\sum_{(s,d) \in \mathcal{T}_t} f_{l^S}^{s,d} \leq x_{l^S} C_{l^S} \qquad \forall l^S \in \mathcal{L_S} \tag{3}$$

$$\sum_{(s,d) \in \mathcal{T}_t} f_{l^I}^{s,d} \leq C_{l^I} \qquad \forall l^I \in \mathcal{L_I} \tag{4}$$

$$f_l^{s,d} \geq 0 \qquad \forall (s,d) \in \mathcal{T}_t, \forall l \in \mathcal{L} \tag{5}$$

The objective function is given by (1), where the main goal is to minimize the network power consumption. In particular, the formulation aims at powering off as many links connecting SDN nodes $l^S \in \mathcal{L_S}$ as possible while respecting both flow conservation (2) and capacity constraints (3-4). Specifically, (3) refers to constraints related to links connecting SDN nodes, whereas (4) acts on the remaining set of links connecting traditional IP nodes. Finally, the positivity constraint represented by (5) forces traffic demands to be non-negative.

Algorithm 1 GA pseudo code description.

Require: A directed graph: $\mathcal{G} = (\mathcal{N}, \mathcal{L})$, a traffic matrix: $\mathcal{T}_t = (s,d)$, number of SDN nodes: θ, selection method: $\mathcal{S}$, population size: κ, number of generations: ρ

1: $P \leftarrow \emptyset, gen \leftarrow 0, sol_{c_P}^t \leftarrow \emptyset, fval_{c_P}^t \gg |\mathcal{L}|$
2: $P \leftarrow createPopulation(\mathcal{G}, \kappa,$ `uniform`$)$
3: **for all** chromosome c_P in P **do** ▷ Evaluate population
4: $\quad (fval_{c_P}, sol_{c_P}) \leftarrow f(c_P, \mathcal{G}, \mathcal{T}_t)$ ▷ Fitness function
5: $\quad$ **if** $fval_{c_P} < fval_{c_P}^t$ **then** ▷ Update best solution
6: $\quad\quad sol_{c_P}^t \leftarrow sol_{c_P}$
7: $\quad\quad fval_{c_P}^t \leftarrow fval_{c_P}$
8: $\quad$ **end if**
9: **end for**
10: **while** $gen \leq \rho$ **do**
11: $\quad parents \leftarrow selectParents(P,$ `roulette`$)$
12: $\quad children \leftarrow performCrossover(parents,$ `single-point`$)$
13: $\quad children^* \leftarrow performMutation(children,$ `uniform`$)$
14: $\quad$ **for all** chromosome c_P in $children^*$ **do**
15: $\quad\quad (fval_{c_P}, sol_{c_P}) \leftarrow f(c_P, \mathcal{G}, \mathcal{T}_t)$
16: $\quad\quad$ **if** $fval_{c_P} < fval_{c_P}^t$ **then**
17: $\quad\quad\quad sol_{c_P}^t \leftarrow sol_{c_P}$
18: $\quad\quad\quad fval_{c_P}^t \leftarrow fval_{c_P}$
19: $\quad\quad$ **end if**
20: $\quad$ **end for**
21: $\quad P \leftarrow replaceChildren(children^*, P)$
22: $\quad gen \leftarrow gen + 1$
23: **end while**
24: **return** $sol_{c_P}^t, fval_{c_P}^t$

III. Genetic Algorithm for Saving Energy in Hybrid IP/SDN Networks

The Multi-Commodity Maximum Flow (MCMF) problem defined in Section II is known to belong to the NP-hard problem class. Therefore, the definition of heuristic solutions is required to be solved on real networks [9]. In particular, we choose to use a GA, whose pseudo code is described by Alg. 1. Six different inputs are needed to invoke it: i) the network graph, $\mathcal{G} = (\mathcal{N}, \mathcal{L})$, with the set of nodes and unidirectional links; ii) a traffic matrix $\mathcal{T}_t = (s,d)$ with the set of traffic demands for each source-destination pair; iii) the number of nodes θ to be considered as SDN nodes; iv) the method $\mathcal{S}$ to select, among the set of traditional IP nodes, those ones to be SDN; v) the population size, κ; and vi) the number of generations, ρ. Initially, a random population, P, of size κ is created with a uniform distribution as in canonic GAs (line 2).

A. Chromosome Definition

A chromosome in the population (search space), $c_P \in P$, is defined as follows:

$$c_P = \left\{g_1, g_2, ..., g_{|\mathcal{L_S}|}\right\}, g_k \in \{0;1\} \tag{6}$$

where the the k-th gene, g_k, represents the operational mode of the k-th link in the set of links connecting SDN nodes, $\mathcal{L_S} \subseteq \mathcal{L}$. Following the classical GA approach, binary values are used to represent the two possible operational modes of each link, $l^S \in \mathcal{L_S}$: $g_k = 0$ (powered off); $g_k = 1$ (powered on). Thus, a particular network configuration is represented by a particular chromosome, c_P, at a given time, t. Note that information related to links $l^I \in \mathcal{L_I}$ is not included in the chromosome definition, since they are always active due to the lack of control by the controller.

B. Fitness Function

A chromosome c_P becomes a potential solution, sol_{c_P}, if the network configuration it represents is able to route the set of traffic demands, $\mathcal{T}_t = (s, d)$, whilst satisfies both flow conservation and capacity constraints.

In order to evaluate the quality of such solution, the definition of a fitness function is therefore required. Indeed, all the individuals belonging to the initial population are evaluated by the fitness function defined in (7), and the best solution found, $sol^t_{c_P}$, is iteratively updated (lines $3-9$, Alg. 1).

$$f(c_P, \mathcal{G}, \mathcal{T}_t) = \left(\sum_{g_k \in c_P} g_k W_{l^S} \right) \psi; \forall l^S \in \mathcal{L}_\mathcal{S}; g_k \in \{0; 1\} \tag{7}$$

The fitness function consists of a sum of the power consumption of all the links connecting SDN nodes, where W_{l^S} refers to the power consumption of link $l^S \in \mathcal{L}_\mathcal{S}$. The simple algorithm used to check chromosome feasibility, with complexity $O(\mathcal{L} \log \mathcal{N})$, and whose result is represented by variable ψ in (7), is summarized as follows: considering that all the links have the same weight, traffic demands are routed on the network configuration represented by the chromosome according to a shortest path rule. If none of the links in the particular configuration is overloaded (i.e. link load is not above a predefined threshold), the chromosome represents a valid solution and $\psi = 1$, otherwise $\psi \gg |\mathcal{L}_S|$. The evolutionary process described in lines $(10-23$, Alg. 1) is divided into ρ generations by applying the inherent genetic functions of GAs: selection (roulette), crossover (single-point), mutation (uniform) and replacement; to finally return the best solution found, $sol^t_{c_P}$.

C. SDN Nodes Selection Methods

Since only the links connecting SDN nodes can be managed by the controller in terms of powering them on/off, the location of the SDN nodes has a strong impact on the energy that can be saved when applying energy-aware approaches. However, the optimum selection of SDN nodes will depend on the traffic pattern which, although it can be gathered from measurements taken in the past and estimated in some way, it will not be known ahead of time. In order to evaluate the influence of the location of the SDN nodes without considering traffic knowledge, three different selection methods ($\mathcal{S}$) are considered:

- **Most Controlled Links First (MCLF)**: The principle of this selection method is to first select the nodes with the highest degree, i.e. with the highest number of links connected to them. The more links the controller is able to manage, the more links that can be powered off, which will lead to an increase in energy savings.
- **Most Non-controlled Links First (MNLF)**: This strategy focuses on separating the SDN nodes sufficiently to have most links under the control of the controller. The process consists on a set of iterations, where the node with the highest number of non-controlled links connected to it is selected as SDN node at each iteration. If a link is not connected to a node selected as SDN node in the previous iterations, it is considered as a non-controlled link. If there are several nodes with the same number of non-controlled links connected to them, the node to become SDN is randomly chosen.
- **Random**: SDN nodes are randomly selected.

For each of the three selection methods described above, a node subset $\mathcal{N}_\mathcal{S} \subseteq \mathcal{N}$ of size $\theta = |\mathcal{N}_\mathcal{S}|$ is returned to be given as input for the proposed GA (Alg. 1). The rest of nodes compose the set of legacy IP nodes, $\mathcal{N}_\mathcal{I} \subseteq \mathcal{N}$, with $\mathcal{N}_\mathcal{S} \cup \mathcal{N}_\mathcal{I} = \mathcal{N} \in \mathcal{G}$. Clearly, $\mathcal{N}_\mathcal{S} = \emptyset$ and $\mathcal{N}_\mathcal{I} = \mathcal{N}$ are the corresponding set of nodes for a traditional IP network that works following OSPF principles. On the other hand, the case of a fully-deployed SDN network is given by $\mathcal{N}_\mathcal{S} = \mathcal{N}$ and $\mathcal{N}_\mathcal{I} = \emptyset$.

IV. Experimental Results

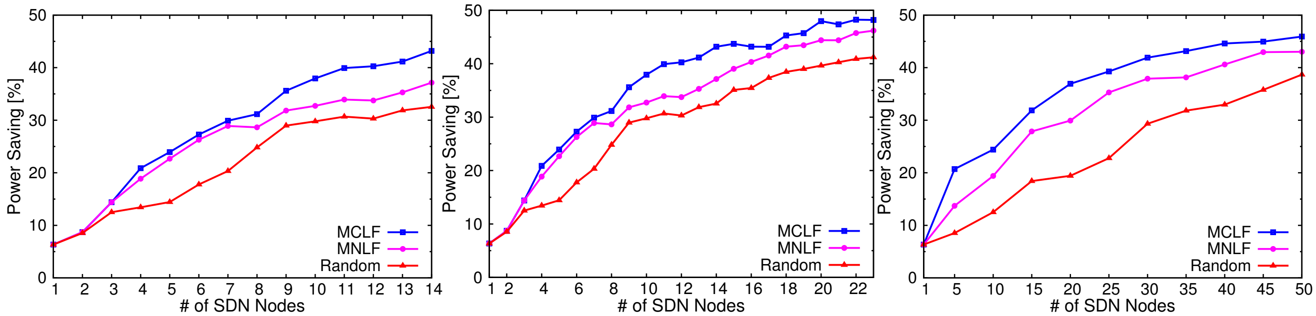
In this section, a performance evaluation of the GA-based heuristic proposed for hybrid IP/SDN networks is provided. A series of simulations have been run over three realistic network topologies, namely NSFNet (14 nodes and 42 links), Géant (23 nodes and 74 links) and Germany (50 nodes and 176 links).

Regarding the network traffic, a daily traffic pattern is assessed for each topology with averaged real data retrieved from [11]. Thus, a set of traffic matrices taken every 5 minutes are provided to give complete coverage for the daily cycle.

Scenarios are composed of a set of θ SDN nodes and a set of $|\mathcal{N}| - \theta$ IP nodes connected by unidirectional links. Link asymmetry is assumed, i.e. the two unidirectional arcs of a link connecting an SDN node can be configured according to different operational modes. Moreover, links power consumption profiles are based on the results section of [12].

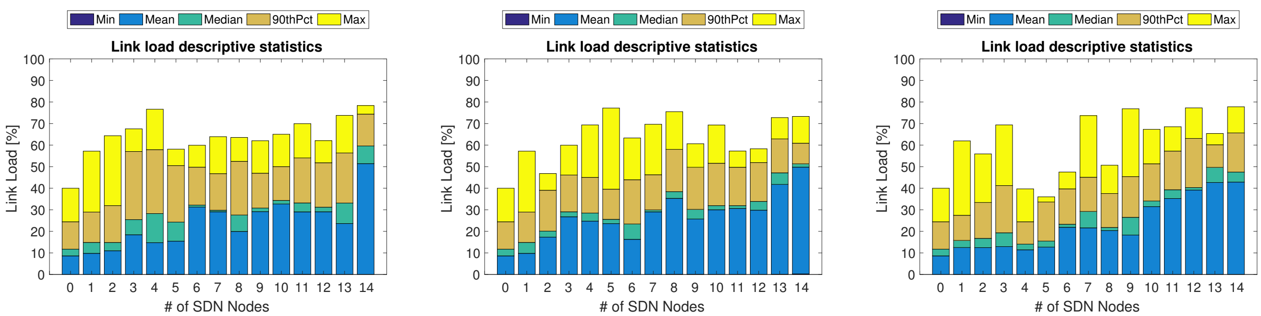
In order to know the impact of using different number of SDN nodes on the energy that can be saved in a hybrid IP/SDN network as well as the selection method to place them, the proposed GA is executed several times varying the values for each parameter considered. Therefore, 50 independent executions have been run for each 3-tuple of type $t_{GA} = \{T, \theta, \mathcal{S}\}$, with T=$\{NSFNet, Geant, Germany\}$; $\theta \in [1, |\mathcal{N}|] \in \mathbb{N}$; and $\mathcal{S}$=$\{MCLF, MNLF, Random\}$. GA parameters were empirically set to: i) Population size, $\kappa = 20$; ii) Maximum number of generations, $\rho = 200$; iii) Crossover probability, $c_{prob} = 20\%$; and iv) Mutation probability, $m_{prob} = 10\%$.

Fig. 1 reports the power saving averaged over the daily cycle as a function of the number of SDN nodes for the three topologies considered. Although the experiments have been repeated 50 times for each value of t_{GA} to assess 95% confidence intervals, error bars have not been included in the figures for the sake of reading. As expected, the power saving increases as a function of the number of SDN nodes, since the higher number of controllable elements in the network, the more opportunities to exploit power-saving techniques.



(a) NSFNet (b) Geant (c) Germany

Fig. 1: Power saving percentage as a function of the number of SDN nodes and selection method.



(a) $\mathcal{S} = MCLF$ (b) $\mathcal{S} = MNLF$ (c) $\mathcal{S} = Random$

Fig. 2: Link load percentage as a function of the number of SDN nodes for NSFNet topology.

Although all the selection methods (even the random one) get comparable power savings when a small number of SDN nodes is considered, MCLF gets, in general, a higher power saving with respect to the other selection methods. In case of Géant and Germany networks, all the selection methods get comparable power saving if a fully-deployed SDN network is considered. For the case of NSFNet network, lower power savings values are obtained, since there are less available links to be to put to sleep by the controller.

Another interesting thing to notice by inspecting Fig. 1 is that, since the curve of the power saving effect follows a (near) exponential shape for a small and medium percentage of SDN nodes (below 60%), a marginal influence over the power saving effect is presented when approaching a fully-deployed SDN network.

It is clear that if a subset of links are powered off to save energy, the rest of active links could experience a link load increase to accommodate the traffic demands. In order to evaluate the impact of applying the GA on the network performance, next analysis aims at evaluating the link load increase experienced by the subset of active links.

Fig. 2 depicts different descriptive statistics related to links load as a function of the number of SDN nodes and the selection method for NSFNet topology. Values reported are averaged over the full set of experiments that were carried out to minimize the power consumption of a hybrid IP/SDN network using the proposed GA.

The first bar of each subfigure refers to the case where no SDN nodes are considered ($|\mathcal{N}_\mathcal{S}| = 0$), i.e. a traditional IP network without the ability of exploiting energy-efficiency techniques. In order to assess link load for this baseline case, a shortest path rule is used to route the traffic matrix. For the rest of the cases, i.e. $|\mathcal{N}_\mathcal{S}| = \{1, ..., 14\} \in \mathbb{N}$, the GA is run as specified in the previous sections. Considering mean and median values, we can see that link load percentage grows with the number of SDN nodes. This is due to the fact that, if the controller is able to manage a bigger subset of links and they are put to sleep, there is a smaller subset of links to accommodate the same amount of traffic. Therefore, link load must be necessarily higher.

However, if we only consider mean and median values, some of the links in the network can be highly loaded but the rest could be prone to be slightly loaded. In this way, maximum and 90th percentile values show most loaded links. We can extract from the figures that maximum link utilization is below 80% for all cases, since this value is the threshold adopted for the link capacity constraints to avoid potential link overloads.

Comparing the three selection methods, it is interesting to remark that link load values obtained when using the

TABLE I: Coefficients[A]

Model	Variable Type	B	Std. Error	Beta	t	Sig.
1 (Constant)		-22.283	2.303		-9.677	.000
Nodes	Continuous	1.546	.301	.432	5.139	.000
Links	Continuous	.435	.085	.432	5.139	.000
Pct10SDN	Categorical	10.335	3.608	.176	2.864	.005
Pct20SDN	Categorical	14.963	3.314	.290	4.514	.000
Pct30SDN	Categorical	21.675	3.314	.459	7.143	.000
Pct40SDN	Categorical	26.039	3.608	.426	6.939	.000
Pct50SDN	Categorical	29.314	3.314	.529	8.241	.000
Pct60SDN	Categorical	35.123	3.314	.680	10.597	.000
Pct70SDN	Categorical	37.115	3.314	.661	10.293	.000
Pct80SDN	Categorical	40.830	3.608	.695	11.315	.000
Pct90SDN	Categorical	41.941	3.608	.714	11.623	.000
Pct100SDN	Categorical	42.535	4.134	.557	9.564	.000
MCLF	Categorical	4.326	3.566	.130	1.213	.028
MNLF	Categorical	3.748	3.566	.113	1.051	.047

[A] Dependent Variable: PowerSavings
Reference Variables: Pct0SDNNodes, Random

Random method (Fig. 2c) are significantly lower than the ones reported for MCLF (Fig. 2a) and MNLF (Fig. 2b), which are very similar. The inherent randomness of the former method to select the SDN nodes differs from the greedy processes followed by the latter ones to choose the best node at each iteration in terms of potential controllable links.

This situation can be explained by inspecting Fig. 1a, where power savings achieved by the proposed GA are reported as a function of the number of SDN nodes for NSFNet topology. Clearly, MCLF and MNLF present higher power saving gains compared to Random method, which means that there are more powered off links for MCLF and MNLF and less active links to accommodate the same amount of traffic. Therefore, link load descriptive statistics are quite higher compared to Random.

In order to statistically validate the previous performance analysis, a multivariate analysis has been performed to assess the impact of each independent variable (number of nodes, number of links, percentage of SDN nodes and selection method) on the selected dependent variable, i.e. the power saving percentage achieved throughout the day. Looking at column B, it is clear that there exists a directly proportional relationship between continuous variables ($Nodes$ and $Links$) and the amount of power savings that can be achieved by the GA. An increase of one unit in the number of nodes in the network is associated in a statistically significant way with an increase of 1.546% in power savings ($.435\%$ in case of links).

Power saving percentage is also analysed when a particular percentage of nodes are considered to be upgraded to SDN. Although it is clear that higher improvements in terms of power savings are obtained for a large number of SDN nodes, the increasing tendency attenuates when the percentage of SDN nodes exceeds a value of 60%. In this way, the energy-saving performance of partially-deployed SDN networks is very close to that of fully-deployed SDN networks, with a gap less than 7.5%. Finally, results obtained by MCLF and MNLF selection methods are about 4 times better than the ones obtained by the random method.

V. Conclusion

In this paper we investigate the problem of minimizing the power consumption of an IP/SDN hybrid network. In particular, the main goal is to evaluate, in terms of energy efficiency, the most appropriate percentage of nodes to be upgraded to SDN and the selection method to place them during the transition from IP to SDN networks. An ILP formulation is presented to solve the optimization problem and a GA-based heuristic is proposed and evaluated through simulations over realistic and different sized network topologies. Results highlight that energy efficiency in hybrid IP/SDN networks could relevantly be improved through the use of a reduced percentage of SDN nodes with a small gap compared to full SDN networks.

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