Green IGP Link Weights for Energy-efficiency and Load-balancing in IP Backbone Networks

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***Abstract*—The energy consumption of backbone networks has become a primary concern for network operators and regulators due to the pervasive deployment of wired backbone networks to meet the requirements of bandwidth-hungry applications. While traditional optimization of IGP link weights has been used in IP based load-balancing operations, in this paper we introduce a novel link weight setting algorithm, the Green Load-balancing Algorithm (GLA), which is able to jointly optimize both energy efficiency and load-balancing in backbone networks. Such a scheme can be directly applied on top of existing link sleeping techniques in order to achieve substantially improved energy saving gains. The contribution is a practical solution that opens a new dimension of energy efficiency optimization, but without sacrificing traditional traffic engineering performance in plain IP routing environments. In order to evaluate the efficiency of the proposed optimization scheme without losing generality, we applied it to a set of recently proposed but diverse algorithms for link sleeping operations in the literature. Evaluation results based on the European academic network topology, GÉANT, and its real traffic matrices show that GLA can achieve significantly improved energy efficiency compared to the original standalone algorithms, while also maintaining near-optimal load-balancing performance.**

***Index Terms*—Green networks, link-weight setting, energy-efficiency, load-balancing.**

I. Introduction

The energy consumption of modern computer networks has become under more scrutiny during the last decade because of the increased pervasiveness of computer networks which consume an excessive amount of power and increase the operational costs of network operators. There is also concern that this increase in energy consumption will lead to more greenhouse gas effects due to the energy being supplied from fossil fuels. European Telecoms currently consume around 21.4TWh per year and this is expected to increase to about 35.8TWh by 2020 if more energy-efficient networks are not deployed [1]. Backbone ISP networks currently consume around 10% of the total network power requirements but this will increase to 40% by 2017 [2] if no green actions are taken. This is largely due to the increasing use of bandwidth-hungry applications such as Video-on-Demand (VoD) and cloud computing over the Internet. In recent years, a number of Energy-aware Traffic Engineering (ETE) schemes have been developed in order to reduce the energy consumption of backbone networks [3][4][8][9][11][12]. These algorithms aim to achieve energy efficiency by means of either putting network devices into sleep mode or adapting the transmission speed of the devices. In order to allow maximum degree of energy efficiency, ETE algorithms have the strategy of intelligently “concentrating” traffic to as small number of network elements as possible, in order to allow more network devices to have the opportunity to save energy, e.g. to go to sleep. As long as the reduced network capacity is sufficient for handling the traffic demand, energy can be saved without causing service deteriorations to end users.

On the other hand, load-balancing has been a common objective of plain traffic engineering in computer networks, and numerous schemes have been developed towards this objective [5]. Load-balancing aims to reduce the Maximum Link Utilization (MLU) in the network through an optimized distribution of traffic. This reduction in MLU allows the networks to offer better Quality of Service assurance and also to efficiently handle unexpected surges in traffic demands. However, since load-balancing attempts to “spread” the traffic while ETE algorithms attempt to “concentrate” traffic only to residual active devices (e.g. network links), conventional load-balancing and ETE are intuitively conflicting each other in network configurations.

In this paper, we present a new algorithm called Green Load-balancing Algorithm (GLA) which jointly optimizes the load-balancing and energy efficiency in the network based on existing ETE schemes. GLA achieves such objectives by optimizing the Interior Gateway Protocol (IGP) link weights of a network, which influences the distribution of traffic in a network. Specifically, intelligent setting of IGP link weights in GLA is able to *maximize energy saving gains* through link sleeping, while *maintaining, or even further improving load balancing performance* on top of the residual working topology. This is in salient contrast to the conventional single-objective IGP link weight setting schemes that do not efficiently provide opportunities for link sleeping operations.

In order to illustrate the basic concept of GLA-based link weight optimization for both load-balancing and energy efficiency, we use the small example network topology in Fig. 1 with indicated link capacities and IGP weight settings. The aim of such an example is to illustrate how IGP link weights can be manipulated in order to create opportunities for more links to sleep, but without affecting the load balancing requirements. For simplicity and clarity, we use an "incomplete" uni-directional graph, but certainly such an idea is also applicable to real network topologies with full bi-directional connectivity. First of all, it can be observed that there are only two links which can be put to sleep without causing the network topology to lose full connectivity: namely links $C \rightarrow D$ and $A \rightarrow D$. We first consider the case where the set of link weights is non-optimized as shown on the left, and then the case where the link weights are optimized on the right side of the figure.

Given a simple illustrative traffic matrix composed of only traffic demands between two Source-Destination pairs: $C - D$ and $A - D$ of 30 and 75 units respectively, the traffic demand $C - D$ goes through path $C \rightarrow D$ with a link utilization of 60%. For the traffic demand $A - D$, path $A \rightarrow D$ is used with a link utilization of 75%. The original MLU in this scenario is therefore 75%. Based on the given traffic demands, we can follow conventional techniques such as [11] to consider link removal one by one from the topology where the least utilized link is selected first. First of all, if link $C \rightarrow D$ is put to sleep, its load is re-routed through the alternative path $C \rightarrow A \rightarrow D$ and the resulting utilization on link $A \rightarrow D$ becomes 105%. Hence, $C \rightarrow D$ cannot be put to sleep because it causes the network to become overloaded. Link $A \rightarrow D$ can be put to sleep because the alternative path $A \rightarrow B \rightarrow D$ will have MLU of 37.5%. Therefore, the resulting MLU in the network is 60% and only one link can be put to sleep.

If the link weights are optimized as shown on the right side of Fig. 1, both links $C \rightarrow D$ and $A \rightarrow D$ can be put to sleep without causing the network to become overloaded. The traffic demands $C - D$ and $A - D$ are routed along the new paths $C \rightarrow A \rightarrow B \rightarrow D$ and $A \rightarrow B \rightarrow D$ respectively. The MLU of the resulting network becomes 52.5% even though two links are now put to sleep. The optimization of the link weights has made it possible not only to reduce the MLU from 75% to 52.5%, but also allows one more link to go to sleep, achieving simultaneous improvement of both load-balancing and energy efficiency objectives.

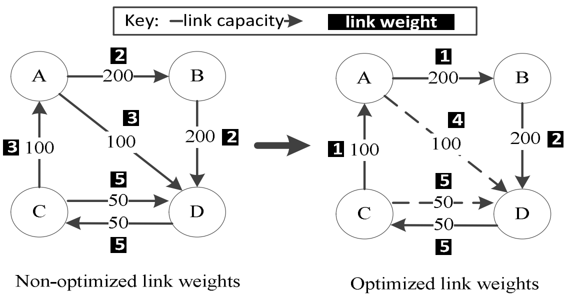

Figure 1. Example network topology to illustrate optimization of link weights.

In addition to the aforementioned simple example that illustrates the effectiveness of GLA based on one snapshot of traffic matrix considered in some simple ETE schemes [11][12], the proposed scheme can be further applied to more advanced approaches which take into account traffic dynamics. According to the Time-driven Link sleeping (TLS) approach [8][9], both the set of sleeping links and their sleeping time are jointly determined by taking into account the patterns of traffic demands for a given period of time. When GLA is to be applied in such scenarios, additional constraints need to be considered. Specifically, a *common* set of IGP link weights needs to be applied across a *diverse* set of traffic matrices. This requires the algorithm to be robust enough to ensure optimized load balancing performance is achieved across different time periods.

Regarding energy saving in a network system, when a network link is configured to the sleep mode, the line cards at both ends of the link are either put to sleep if the line cards have no other active links connected to them, or they can enter a lower power mode because an interface becomes inactive. Putting a whole line card or one of its interfaces inside the router to sleep is the main source of energy saving in a backbone network because fiber links along with their amplifiers account for only 7% of the power budget of a network [6] with the remaining 93% energy being consumed by routers. The line cards inside an IP router typically consume around 43% of the total power of the router [7] and therefore, significant energy efficiency can be achieved by putting links into sleep mode because of the effect it has on the power consumption of line cards.

II. RELATED WORK

The field of Energy-aware Traffic Engineering (ETE) started with the seminal work in [8] where the authors explore how traffic can be re-routed so as to promote energy efficiency in network devices. Since then, numerous ETE schemes have been developed and summarized in the two surveys [3] and [4]. The different ETE schemes can be classified as either offline or online. Offline ETE schemes ([7][9][10][11][12][13][14]) usually compute static network configurations based on forecasted traffic matrices. These schemes offer the advantage of practical deployment based on existing network devices and protocols. Another advantage of offline schemes is that they can achieve higher energy efficiency and traffic performance due to the use of global optimization techniques thanks to the availability of a complete view on the network state. Offline ETE schemes are often implementable with the use of long-established protocols and therefore, more likely to be adopted by network operators. On the other hand, they are more vulnerable to dynamic, especially unpredicted, traffic behaviours.

On the other hand, online ETE schemes ([8][15][16][17][18][19][20]) continuously monitor the state of the network on a shorter timescale which allows them to make on-the-fly re-configurations of the network. They are more agile to unexpected traffic dynamics, but they do suffer from a limited knowledge of the network state when computing a new configuration. Similar to plain online traffic engineering (TE) techniques, online ETE mechanisms rely on accurate network monitoring and face additional challenges such as network stability and necessary requirements on protocol extensions. This makes the online ETE solutions more difficult to be deployed than their offline counterparts.

It is worth mentioning that, most offline ETE schemes ([9][10][11][12][13][14]) are based on IGP routing. When these offline ETE schemes perform link sleeping in order to reduce the energy consumption of backbone networks, they do NOT consider the scenario of manipulating the IGP link weights in order to optimize their performance. Our new algorithm, Green Load-balancing Algorithm (GLA), proposes the optimization of the IGP link weights so as to optimize the traffic distribution in the network, and also substantially improve the energy saving gains as compared to existing ETE schemes.

III. Problem Formulation and Existing ETE Schemes

A. Problem Formulation

TABLE I. DEFINITION OF SYMBOLS

Variable	Description
$G(N, L)$	Directed graph with N being set of nodes and L being set of links
U	Maximum link utilization
E	Energy efficiency
c_{ij}	Bandwidth capacity of link from node i to j
t^{sd}	Traffic demand from node s to d
f_{ij}^{sd}	Traffic demand from s to d that traverses link from i to j
f_{ij}	Total traffic demand on link from i to j
α	Maximum allowable utilization of link capacity

The joint-optimization of load-balancing and energy efficiency in a network can be expressed with the following two objectives:

$$\text{minimize } U \tag{1}$$

$$\text{maximize } E \tag{2}$$

subject to:

$$\sum_{j=1}^{|N|} f_{ij}^{sd} - \sum_{j=1}^{|N|} f_{ji}^{sd} = \begin{cases} t^{sd} & \forall s, d, i = s \\ -t^{sd} & \forall s, d, i = d \\ 0 & \forall s, d, i \neq s, d \end{cases} \tag{3}$$

$$f_{ij} < \frac{\alpha}{100} \times c_{ij} \quad \forall i, j \text{ with } \alpha \in [0,100] \tag{4}$$

Equation 1 represents the first objective of GLA which is the minimization of the Maximum Link Utilization (MLU) in the network in order to achieve load-balancing. For the GLA scenarios based on one traffic matrix, it refers to the MLU related to that snapshot only. For the GLA involving multiple traffic matrices (e.g. based on TLS), this refers to the *worst-case scenario* across all considered traffic matrices. Equation 2 represents the second objective of GLA which is the maximization of the energy saving gains given by an existing ETE scheme. Again, the definition of E is specific to individual ETE schemes we consider, which will be introduced in Section III. B. Equation 3 represents the standard flow conservation constraint. Equation 4 ensures that whenever a reduced topology is used, all active links should have their utilization below a given threshold determined by the ISP. That is, with a set of links being put into sleep mode, the maximum link load should not exceed the threshold α (in terms of the fraction of the link capacity). Another constraint is that the network needs to remain fully connected when links are configured to sleep mode so that there is always a path between any two nodes in the reduced network topology.

B. Existing ETE Schemes

Here we give a brief review of the three different offline ETE schemes based on which GLA is applied. The first two schemes, Least Flow (LF) and Most Power (MP), were introduced in [11] and [12] respectively. The third ETE scheme on which GLA was evaluated is Time-driven Link Sleeping (TLS) which is our own ETE scheme and was introduced in [9] and [10]. The major difference between the first two schemes and TLS is that the first two schemes operate on one single traffic matrix snapshot at a time and do not consider a collection of *dynamic* traffic matrices as TLS does. It is also worth mentioning that each of these three schemes has a different way of calculating the Eq. 1 and 2 in Section III. A.

1) The Least Flow Scheme

In [11], the authors use an ETE scheme called Least Flow (LF). LF iteratively selects the least loaded link in the network as candidate for sleeping. The selected link can only go to sleep if the full connectivity of the network topology is maintained and the resulting MLU is below a given threshold when the link enters sleep mode. Otherwise, the next least loaded link is selected for sleeping consideration until all the links have been investigated.

During the operation of GLA on top of LF, the value of Eq. 1 is the MLU value when the single traffic matrix is mapped onto the network with its full topology. The MLU value obtained is then used as the value of α in Eq. 4. The energy efficiency (value of Eq. 2) of LF is calculated as shown by Eq. 5 where $|B|$ is the number of sleeping links and $|L|$ is the total number of links in the network.

$$E = \frac{|B|}{|L|} \tag{5}$$

2) The Most Power Scheme

The Most Power (MP) ETE scheme presented in [12] is similar to LF. MP iteratively selects the link which consumes the highest amount of power in the network as candidate for sleeping. The selected link can only go to sleep if the full connectivity of the network is maintained and the resulting MLU is below a given threshold when the link is sleeping. Otherwise, the next link which consumes the most power becomes candidate for removal.

During the operation of GLA on top of MF, the value of Eq. 1 is calculated in the same way as for the LF algorithm above. The MLU value obtained is then used as the value of α in Eq. 4. The energy efficiency (value of Eq. 2) of MP is calculated as shown in Eq. 6 where P_l is the power consumed when the link with index l is active and B is the set of links that are sleeping. As mentioned in Section I, the energy savings due to a link being put into sleep mode can pre-dominantly be attributed to the line cards which are connected to the link.

$$E = \frac{\sum_{l=0:l\in B}^{|L|} P_l}{\sum_{l=o}^{|L|} P_l} \quad (6)$$

3) The Time-driven Link Sleeping Scheme

The main design principle of TLS [8][9] is that sometimes it is not practical to re-calculate the links to go to sleep for each traffic matrix at short-time scale due to stability requirements in the network.

It has been observed that many operational networks ([21] [22][23][24][25]) exhibit a regular diurnal traffic pattern where the traffic demands are high during the day and low during the night. TLS takes advantage of this traffic pattern by having two network configurations: "full network topology" and "reduced network topology". The "full network topology" is the network configuration where all the links in the network are active while the "reduced network topology" is the network configuration where some links are put to sleep for energy efficiency. The first configuration is used during peak time and the second one during off-peak time. The TLS algorithm is responsible for jointly determining both the sleeping link set and its sleeping duration, which is effectively the duration of the off-peak time.

In the operation of GLA on top of TLS, the objective value, U, in Eq. 1 is equal to the worst-case MLU in the network when all traffic matrices are considered. Specifically, the metric U in Eq. 1 represents the *peak-time* MLU in the network to be optimized. The MLU constraint for the off-peak time, represented by α in Eq. 4, depends on either the obtained peak-time MLU or is pre-determined by the network operator. The energy efficiency (value of Eq. 2) of TLS is calculated according to Eq. 7, where $|B|$ is the number of sleeping links in the "reduced network topology", T_{op} is the time duration during which the "reduced network topology" is operated, $|L|$ is the total number of links in the network and T is the total operation time under consideration. According to Eq. 7, the energy efficiency of TLS can only be increased by increasing the nominator in Eq. 7 since the denominator is fixed. Intuitively, an increase in the number of sleeping links may lead to a smaller off-peak duration (i.e. sleeping time T_{op}), because the capacity of network is reduced and only a smaller number of traffic demands can now be satisfied. Therefore, a trade-off needs to be obtained between $|B|$ and T_{op}.

$$E = \frac{|B| \times T_{op}}{|L| \times T} \quad (7)$$

IV. GREEN LOAD-BALANCING ALGORITHM

A. Algorithm Overview

It is well-known that computing the optimal link weights for basic load-balancing is already an NP-hard problem [26], and here we propose an algorithm, Green Load-balancing Algorithm, which is based on meta-heuristics (evolutionary/genetic algorithms) to find the optimized IGP link weights which can solve the more complicated problem of the joint-optimization of load-balancing and energy efficiency in a backbone network.

GLA is used to solve the problem of finding the set of optimized green IGP link weights which caters for both objectives 1 and 2 as represented by Eq. 1 and 2 respectively in Section III. A. GLA is implemented in the form of a customized version of the Non-dominant Sorting Genetic Algorithm (NSGA-II) [27]. NSGA-II operates in a similar fashion to traditional genetic algorithms. NSGA-II has been chosen because it is a multi-objective algorithm which preserves diversity and elitism of the solution space and has low computational complexity. NSGA-II can be used to find the Pareto-optimal front of a solution space. This Pareto-optimal front arises due to the presence of two objectives in the problem formulation, load-balancing and energy efficiency. Intuitively, load-balancing and energy efficiency through link sleeping are two conflicting objectives. This is because load-balancing aims to reduce the load on highly-utilized links by shifting the traffic demands on these links to less utilized links in the network while energy efficiency requires the traffic to be concentrated on a subset of active links and putting the non-utilized links to sleep, which results in the active links becoming highly-utilized. The conflict between the two objectives gives rise to a Pareto-optimal front in the sense that, when the MLU is reduced for load-balancing purposes, the energy efficiency objective will be sacrificed because of the more constrained environment for the different ETE schemes. Hence, an optimized trade-off needs to be obtained between these two objectives. In addition to the basic NSGA-II operations, two custom operators are also introduced to further enhance its performance through more efficient search in the solution space.

B. Solution Encoding

In the genetic algorithm, the solution (i.e. the set of IGP link weights in GLA) is encoded through a chromosome. A chromosome is made up of a number of genes, which is equal to the number of links in the network in our case. Therefore, each gene in the chromosome represents a link in the network. Each gene is restricted to an integer value in the range of 1 to 65535. This range corresponds to the range of values allowed for IGP link weights. In our algorithm, a link with a link weight of 65535 is defined as sleeping and is not used to route traffic demands.

C. Fitness Functions

Each chromosome (i.e. solution candidate) has two distinct fitness functions in the NSGA-II algorithm which are represented by Eq. 1 and 2 in Section III. A respectively. As mentioned previously, since the three ETE schemes, described in Section III. B, have different mechanisms, their fitness functions differ in the way they calculate Eq. 1 and 2 as described in Section III. B.

D. Sleeping Link Crossover Operator

A crossover operation in a genetic algorithm involves taking two chromosomes (i.e. two solutions) in the current population (set of solutions) and swapping their genes (i.e. link weights) with each other to produce two new offspring chromosomes. The aim is to produce newly generated solution candidates with better fitness values. In order to explore the solution space more efficiently and achieve quicker convergence, a customized crossover operator is designed in addition to the standard operators such as two-segment crossover. This new crossover operator has been designed so that one parent chromosome can replace its gene with its counterpart gene in the other parent chromosome if the counterpart gene represents a sleeping link.

Fig. 2 shows the operation of the new crossover operator. A chromosome in this operation is made up of two rows. The top row contains the IGP link weights while the bottom one contains a binary array which indicates link status. A "1" value means that a link is sleeping and "0" means the link is active. The IGP weight of an active link in a chromosome is changed with its counterpart in the other parent chromosome only if its counterpart is marked as sleeping. The arrows between the two parent chromosomes in Fig. 2 show when link weight change occurs and the direction of the change. This operation is similar to "XORing" the bottom row of the two parent chromosomes. This new crossover operator allows "good" link weights which promote link sleeping to propagate through the population.

E. Link Utilization Mutation Operator

A mutation operation in a genetic algorithm involves taking one chromosome (i.e. solution candidate) in the population and modifying one or more genes (i.e. link weights) in the chromosomes. This operation is done so that new genes, which do not exist in the current population, are introduced in the population with the aim that this will increase the fitness functions of the selected chromosomes. A new mutation operator has been developed based on the percentage utilization of each link when a traffic matrix is mapped onto the topology. In this new mutation operator, each link weight has P_{umut} probability of mutating which is equal to the utilization percentage of that link divided by the MLU in the network. As such, highly utilized links will have a higher probability of mutating compared to links with low utilization. The probability that a chromosome in the parent population will begin this utilization-based mutation is given by $P_{mut}/2$ where P_{mut} is the probability of a chromosome undergoing mutation and there is $P_{mut}/2$ probability that the chromosome will undergo the other standard mutation operators.

If a link is selected to be mutated, its link weight will be increased according to Eq. 8 where W_n is the new link weight. W_o is the old link weight and is used as the mean of a normal distribution D with standard deviation εW_o where ε is a fractional multiplier lower than 1.

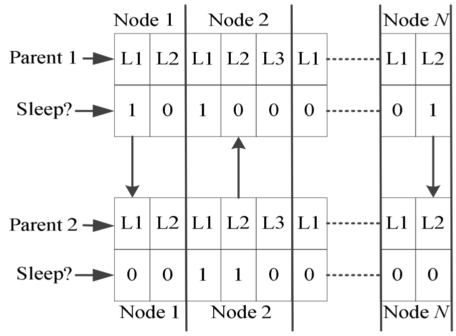

Figure 2. Sleeping link crossover operator.

The rationale behind Eq. 8 is that highly utilized links will have their link weights increased, and hence make them less likely to be chosen by IGP for routing traffic demands. This is likely to cause the load of these links to decrease if alternative shorter paths are identified to route the traffic demands.

$$W_n = W_o + |W_o - D(W_o, \varepsilon W_o)| \quad (8)$$

F. Overall Operation of GLA

At the beginning of GLA, an initial population of random chromosomes is generated. An offspring population is then created through the joint application of crossover and mutation operators on some randomly selected chromosomes in the parent population. In addition to the traditional crossover and mutation operators such as two-segment crossover and random gene mutation, the two custom crossover and mutation operators, described in the previous two subsections, are applied. These customized genetic operators help the exploration of the search space in a more efficient manner. The parent and offspring populations are then merged and sorted according to the fitness and diversity scores of the individual chromosomes to create a new parent population. The algorithm stops when a given targeted number of generations has been calculated, or there has been no improvement in the obtained solutions since a given number of generations.

V. PERFORMANCE EVALUATION

A. Network Scenario

We evaluate the performance of GLA on top of different ETE schemes ([3][4][8][9]) by using the operational network topology, GÉANT and its published traffic matrices [28]. GÉANT is a European academic network which has allowed researchers access to its network topology and traffic matrices. The published topology consists of 23 Points-of-Presence (PoPs) and 74 unidirectional links of varying bandwidth capacities which are described in Table II below. The total power consumption due to a link being put into sleep mode is also given in the table. These values were calculated from the power consumption model of line cards in [29] with the assumption that line cards are responsible for most of the energy consumption of a link [6][7]. The power values are used by the 2nd ETE algorithm, MP, to decide which link to put to sleep first.

TABLE II. POWER USED DUE TO AN ACTIVE LINK

	Number of links, L	Bandwidth (Mbps)	Power, P (W)	L x P (W)
	32	9953	1120	35840
	2	4876	560	1120
	32	2488	280	8960
	8	155.2	98	784
Total	74			46704

TLS operates on a collection of traffic matrices by nature and therefore, we consider 480 consecutive traffic matrices at 15-minute intervals from Monday midday to Saturday midday according to the historical GÉANT traffic matrix data set [28]. The statistical characteristics of the traffic matrices during this period are given in Table III. ETE schemes using LF and MP only focus on each standalone traffic matrix. We choose 10 traffic matrices from the set of traffic matrices used to evaluate TLS. The 10 traffic matrices were chosen by taking 2 traffic matrices each from the subset of traffic matrices which has a MLU close to the Max., Min., Mean and 1st and 3rd Quartiles MLU as specified in Table III.

TABLE III. CHARACTERISTICS OF SET OF TRAFFIC MATRICES FOR EVALUATION OF TLS

MLU	Value (%)
Max.	90.9
Min.	30.9
Mean	58.6
1st Quartile	44.5
2nd Quartile	55.9
3rd Quartile	74.2

There are three different sets of link weights which are compared in this paper: *Default*, *Interior Gateway Protocol Weight Optimizer (IGP_WO)* and *GLA*. The Default link weights are the actual link weights applied in practice. IGP_WO contains link weights which are optimized following [26] for general load-balancing purpose only, without any energy awareness. These two link weight setting strategies are used as benchmarks to evaluate the energy saving gains obtained by GLA based on common ETE schemes.

GLA is run with 10 different seeds to get the average performance. As mentioned previously, GLA produces a set of Pareto-optimal solutions for each seed. Each solution candidate shows a different trade-off between energy-savings and load-balancing. As we aim to achieve energy efficiency without substantially sacrificing conventional traffic engineering (i.e. load balancing) performance, we decided to exclude all solutions which have an MLU which is Ψ% (e.g. 3% in our evaluation scenarios) above the lowest MLU given by the GLA link weights. For each seed, the best solution is then chosen by identifying the solution among the remaining solution candidates which has the lowest ratio of MLU to energy efficiency. TLS was further evaluated by having different MLU constraints, represented by α in Eq. 4, during off-peak time where the "reduced network topology" is applied. The different off-peak MLU constraints represent the different degrees of conservativeness by the network operator during off-peak time.

B. Simulation Results

Table IV demonstrates the performance of the three sets of link weights for the ETE schemes LF and MP specified in Section III. B. The performance is measured in terms of the average change in Maximum Link Utilization, $\boldsymbol{\Delta U}$, and average change in energy efficiency, $\boldsymbol{\Delta E}$, when compared to the results given by the Default link weights. In the case of LF, the number of sleeping link computed by GLA has increased by 16.1% while reducing the MLU by 30.7% compared to the results given by the Default link weights. This shows that GLA can reduce the MLU while still achieving significantly higher energy efficiency. IGP_WO link weight setting was not able to improve the energy efficiency after the MLU in the network has been reduced. This is shown by the negative sign for $\boldsymbol{\Delta E}$. It is observed that GLA performs slightly better than IGP_WO in terms of load-balancing even though GLA considers energy-savings at the same time. For MP, the amount of energy saved by GLA has increased by 1.08% while reducing the MLU by 31% compared to the results given by the Default link weights. When IGP_WO link weights were used, it was still not able to improve the energy efficiency when the MLU of the network is reduced.

TABLE IV. PERFORMANCE COMPARISON OF THREE SETS OF LINK WEIGHTS FOR LF AND MP

	IGP_WO		GLA	
	$\boldsymbol{\Delta U}$ (%)	$\boldsymbol{\Delta E}$ (%)	$\boldsymbol{\Delta U}$ (%)	$\boldsymbol{\Delta E}$ (%)
LF	-27.1	-1.17	-30.7	16.1
MP	-27.1	-14.3	-31.0	1.08

Regarding TLS, Fig. 3 shows that GLA can achieve a substantial improvement in energy efficiency of 238% and 144% compared with Default and IGP_WO link weights respectively when α (in Eq. 4) is set equal to the worst-case MLU given by the "full network topology", U. Effectively, α represents the worst-case MLU that can be observed during the entire off-peak operation duration of the "reduced network topology". Similar observation is obtained when α is further reduced to 65% and 60% respectively. The energy efficiency decreases when α is decreased because of the more conservative constraint for TLS. Table V shows that the high energy efficiency obtained using GLA is not at the expense of load-balancing since the GLA values for load-balancing are lower than those for IGP_WO.

Fig. 4 shows the actual MLU performances across the 5 days when Default, IGP_WO and GLA link weights are applied to the network. It is interesting to see that when α is set equal to U, the off-peak duration of GLA is even able to cover the entire 5-day period because the difference between the peak and off-peak MLU under GLA is zero (also see Table V). It is acceptable for a network to not use some links at all because this will reduce the operational costs even if the network operator has already invested capital in the network. The network operator can put the always-sleeping links back on when there is a need for extra capacity in the network. When α is set below U, link sleeping can be only configured within a specific period on daily basis. This is shown by the dark areas for the Default scenario in Fig. 4 and for the GLA link weights in Fig. 5 where α is set equal to 60%.

The performance of the reduced network topology, obtained by GLA on top of TLS, during single link failures can be guaranteed by using an extended version of TLS called Time-driven Link Sleeping with Single Link Failure Protection (TLS-SLFP) published in [9]. GLA can operate with no modification on top of TLS-SLFP and this will be studied in our future work along with our own extension of the LF and MP schemes to support single link failures.

VI. Enhanced GLA for TLS

A. Solution-enhancement Heuristic

The performance of GLA for TLS can be improved further if GLA is further customized for TLS through the use a Solution-enhancement Heuristic (SH). This enhanced version of GLA is called Green Load-balancing Algorithm with Solution-enhancement Heuristic (GLA-SH) and is designed to run at the end of each iteration of GLA. SH operates on the best solution in the population at the end of each iteration. The best solution is determined by a single aggregated objective function represented by the ratio of Maximum Link Utilization to energy efficiency as given by Eq. 1 and 2 in Section III. A respectively. Fig. 6 shows the operation flowchart of SH. The chromosome (i.e. solution candidate) selected for improvement is first evaluated to find the size of the off-peak duration. In TLS, the energy efficiency is effectively represented by the number of sleeping links multiplied by the off-peak duration.

If the length of the off-peak duration is at its maximum, the duration cannot be further increased to improve the energy efficiency. The only option is to increase the number of sleeping links instead. This involves diverting load from certain active links in order to enable them to sleep. This diversion of load is done through the increase of the IGP link weights of certain links. SH first identifies the traffic matrix which gives the worst-case MLU when its traffic demands are routed with the off-peak “reduced network topology”. The next step involves the creation of a list of active links ranked in ascending order according to the utilization of the links. The first link in the list is the least utilized in the network and therefore, it is easier to shift its load to other links. This link will be first chosen to have its link weight increased. After each link weight increase, the modified chromosome is re-evaluated to see if the energy efficiency has improved and the worst-case MLU has remained the same or has been reduced. If these criteria are met, SH stops and returns the improved chromosome to the population where it will replace the currently worst chromosome. In the case of the criteria not being met, the link weight of last modified link is restored to its original value and the next link in the list undergoes link weight increase. This process continues until either all the links in the list have been tested or improvement of the chromosome has been successful.

TABLE V. Performance of GLA for the three set of link weights

α (%)	Default		IGP_WO		GLA	
	U (%)	E (%)	U (%)	E (%)	U (%)	E (%)
69.7	90.9	13.5	70.1	18.7	69.7	42.7
65.0	90.9	11.1	70.1	16.9	69.5	39.3
60.0	90.9	10.2	70.1	12.8	69.6	34.7

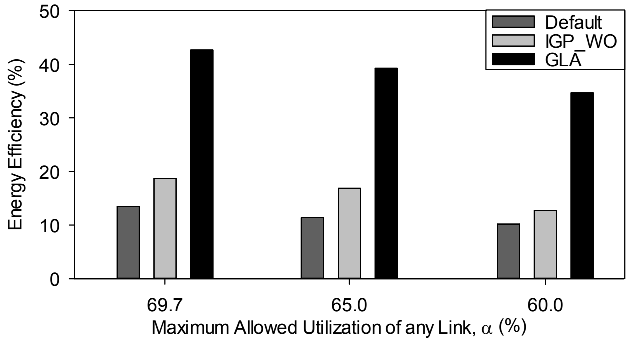

Figure 3. Energy efficiency of TLS using the different sets of link weights.

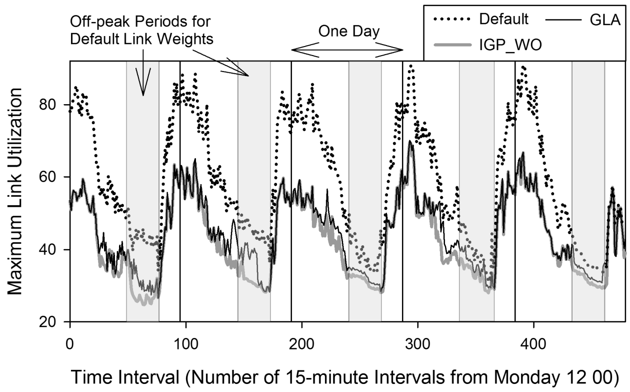

Figure 4. The MLU variation across 5 days for Default, IGP_WO and GLA link weights when α is set equal to U.

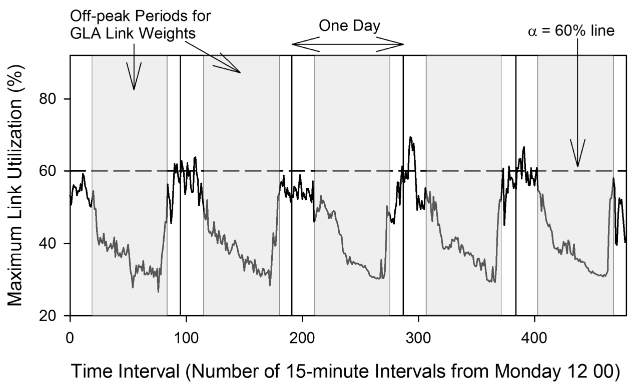

Figure 5. The MLU variation across 5 days for GLA link weights when α is set equal to 60%, which is below U.

If the size of the off-peak duration is not at its maximum, the energy efficiency can be improved through the increase of the length of the duration of the off-peak period. The traffic matrices at the edges of the off-peak periods are first evaluated according to the off-peak "reduced network topology" to see which one gives the worst-case MLU. The identified traffic matrix is the one which has most likely caused the off-peak duration to be small because the maximum allowable utilization of any link in the network has been reached. The traffic demands of the identified traffic matrix are then routed and a list of active links is created. This time, the list is sorted in descending order according to utilization percentage. This is because the MLU can be reduced to allow the off-peak duration to increase for more energy efficiency gains. This is achieved by shifting load from the most utilized link by increasing its link weight. The same iterative process of link weight increase is then performed in the same manner as in the previous case. Chromosomes which cannot be improved by SH are tracked so that SH does not run on them again and the next best chromosome is used as candidate for improvement by SH.

It is worth noting that it is possible to introduce solution enhancement heuristics for other ETE algorithms as well. These solution enhancement heuristics need to be specifically designed by taking into account their own working mechanisms in question. The development of such heuristics is however outside the scope of this paper.

B. Evaluation

The GLA-SH was evaluated using the same network scenario as described in section V. B. The results from Table VI and Fig. 6 show that GLA-SH can increase the energy efficiency of TLS by 7% compared to plain GLA when α is set equal to U. The improvement when α is set to 65% and 60% is 9.41% and 15.6% respectively. These results show that the Solution-enhancement heuristic can improve the energy efficiency of TLS by customizing the operation of GLA.

VII. CONCLUSIONS

In this paper, we proposed a new algorithm, Green Load-balancing Algorithm (GLA), which jointly optimizes the load-balancing and energy efficiency of existing ETE algorithms in IP backbone networks. GLA can work on top of a wide variety of existing ETE algorithm which uses IGP routing and achieves energy efficiency through link sleeping.

Since optimization of link weights is an NP-hard problem, GLA uses a customized multi-objective genetic algorithm to find the optimized solutions. The performance of the genetic algorithm has been improved through two new custom mutation and crossover operators which have been designed so that the solution space can be searched more efficiently. GLA was evaluated on top of three different existing ETE schemes: LF, MP and TLS.

The simulation experiments were performed based on the GÉANT network topology and its real traffic matrices. GLA is shown to improve the energy efficiency of LF, MP and TLS by 16.1%, 1.08% and 216% respectively compared to the Default link weight setting scenario. This improvement has been achieved while maintaining near-optimal load-balancing performance as shown through a comparison with IGP_WO. An enhanced version of GLA, GLA-SH, was also designed specifically for TLS. GLA-SH has been able to improve the energy efficiency of TLS by 239% compared to the Default link weight setting, while maintaining near-optimal load-balancing performance.

GLA can be viewed as a very promising approach which is able to further enhance the performance of ETE algorithms while maintaining at the same time the capability of the produced network configurations towards supporting traditional traffic engineering objectives such as load-balancing.

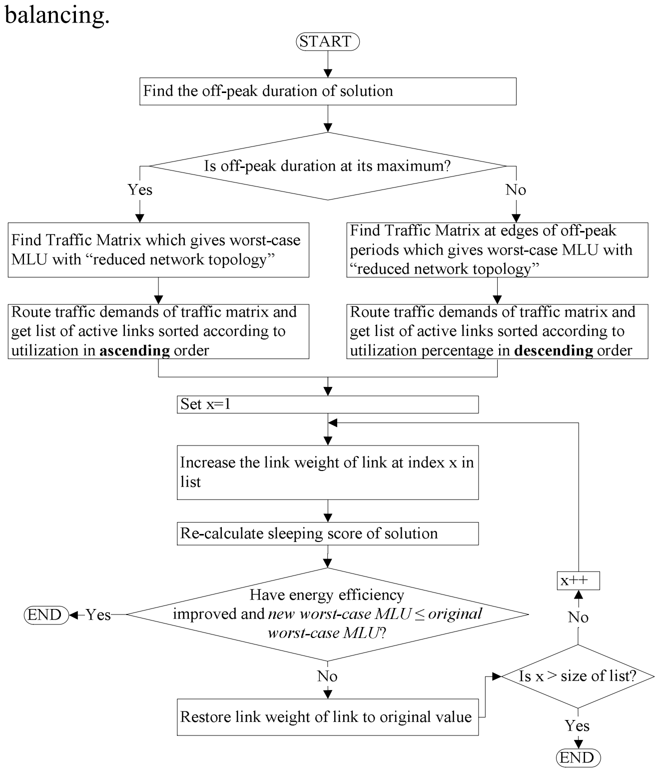

Figure 6. Flowchart describing the operation of the Solution-enhancement heuristic.

TABLE VI. COMPARISON BETWEEN GLA AND GLA-SH

α (%)	GLA		GLA-SH	
	U (%)	***E*** (%)	***U*** (%)	***E*** (%)
69.6	69.7	42.7	69.6	45.7
65.0	69.5	39.3	69.5	43.0
60.0	69.6	34.7	69.5	40.1

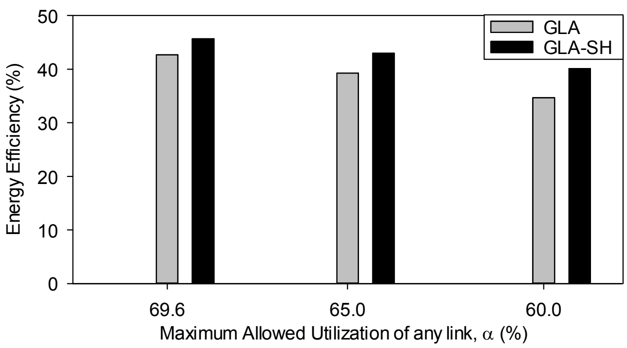

Figure 7. Comparison of energy efficiency between GLA and GLA-SH.

ACKNOWLEDGMENT

The research leading to these results has been performed within the UniverSelf project (www.UniverSelf-project.eu) and received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 257513. In addition, this project received support from EU FP7 IRSES EVANS project (PIRSES-GA-2010-269323).

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