An Optimization Framework for the Energy Management of Carrier Ethernet Networks with Multiple Spanning Trees

Antonio Capone, Daniele Corti, Luca Gianoli, Brunilde Sansó *

Abstract

We propose an energy management framework to optimize the energy consumption of networks using the Multiple Spanning Tree Protocol such as Carrier Grade Ethernet networks. The objective is to minimize the energy consumption of nodes and links while considering QoS constraints. The energy management is done through the Multiple Spanning Tree Protocol (MSTP) by choosing from a given set the most appropriate spanning trees and the most appropriate edges to operate while respecting the traffic demands. A trade-off framework between energy consumption and network performance is proposed. Results show that it is possible to achieve a good traffic engineering while operating the network closer to the minimum energy value.

1 Introduction

The Internet is a highly energy consuming system given the large number of devices involved in its operation. According to [7], [13] and [24], the current Internet consumption represents at least 2% of the total energy consumption of the planet and up to 100 billions kWh (10^{14} Wh) in the US. One billion kWh/yr corresponds to 85 million dollars and about 0.75 million tons of CO_2 [22], which makes Internet consumption an important economic and environmental issue.

*A.Capone and D. Corti are with the Politecnico di Milano, Italy. B. Sansó is with the École Polytechnique de Montréal, Canada. L. Gianoli is on a joint PhD program with the Politecnico di Milano and the École Polytechnique de Montréal. Corresponding author: prof. Antonio Capone, DEI - Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133, Milan, Italy, email: antonio.capone@polimi.it.

Even though important results have been obtained to increasingly improve the energy efficiency of wireless devices, only recently the energy efficiency of the wired networks has become an important issue [23]. The majority of the power is supposed to be consumed by the metro and access networks [8] and, according to [15] the bandwidth requirements of networking applications are doubling every 18 months. In the coming years global Internet traffic will likely present a similar or higher growth rate, and it is expected that this will also result in an increase in the network total power consumption because of the additional devices needed and their higher consumption for higher capacity. On the other hand, the foreseen evolution of the network involves the deployment of Next Generation Access Networks (NGAN) that are expected to bring greater energy efficiency and to enable higher Internet speed, through the progressive deployment of optical fibre. In several network segments, including metro networks and backbone networks, the use of Ethernet as a Carrier Grade technology is becoming very popular due to its low cost and flexibility.

The aim of this paper, that is based on the preliminary work presented in [14, 11], is to exploit the features of Carrier Grade Ethernet networks to reduce energy consumption while guaranteeing network performance. For this, we propose an optimization framework that specifically makes use of the Multiple Spanning Tree Protocol network architecture to optimize overall energy consumption. The reminder of the paper is divided as follows. Section 2 provides an overview of the Gigabit Ethernet Technology and the evolution of the Spanning Trees protocols, that are at the core of the network architecture. Section

3 is devoted to a literature review on the two themes that are related to our framework: green networking problems in wired networks and design and traffic engineering models for ethernet networks. The optimization framework is introduced in Section 4 where we first present the energy-aware optimization model and, next, explore some traffic engineering variations. The computational results are presented in Section 5 whereas Section 6 concludes the paper.

2 Preliminaries

2.1 The GbE technology

Ethernet is a plug'n'play technology at the link layer developed to provide connectivity in LANs. Originally set to 10 Mb/s in the 1980s by the Ethernet physical layer 802.3 standard, its transmission rates have evolved to higher speeds, reaching 100 Mb/s and 1 Gb/s and finally 10 Gb/s with the IEEE 802.3ae standard in 2002 and the EPON access environments oriented standard (802.3av) in 2009.

Despite its popularity as a LAN technology, Ethernet needed an enhancement to be used in Carrier Grade networks. Traditional Ethernet lacks essential transport features such as wide area scalability, resilience and fast recovery from network failures, operation, administration and maintenance capabilities, admission control and advanced traffic engineering functionality, such as load balancing. Ethernet is expected to play an important role in broadband networks through the implementation of Carrier Grade Ethernet (CGE) which regroups a number of industrial and academic initiatives aiming at equipping Ethernet with the transport features listed above. Ethernet is considered such an attractive technology because of the promise of a reduced protocol stack. Moreover, it provides very high speeds with copper or low-cost optical interfaces and its management is very simple, therefore, the reductions in cost and complexity are expected to be considerable. For instance, in [25], the authors show that implementing CGE could result in 40% port-count reduction and 20–80% CAPEX drop compared to various non-Ethernet backbone technology alternatives.

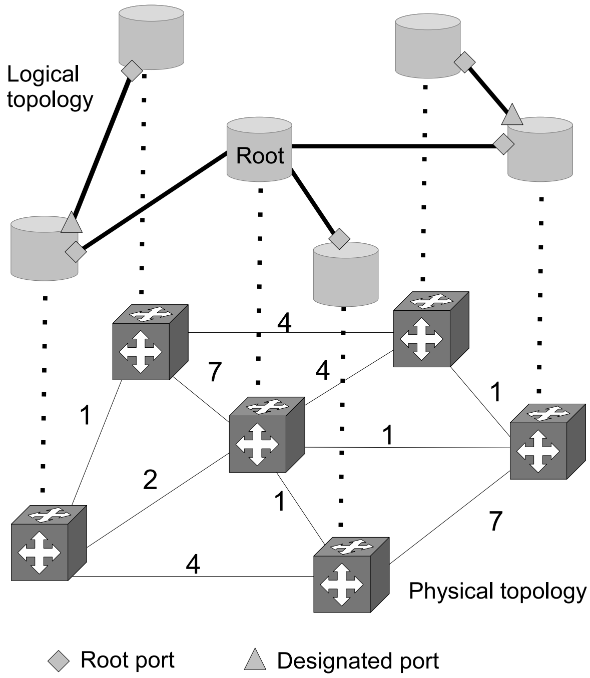


Figure 1: Logical topology consisting in a Spanning Tree built over a physical topology. No loops are present. The distances between the root and the root ports are calculated according to the weights reported near the links.

The IEEE, ITU-T, IETF and Metro Ethernet Forum (MEF) are currently working on a set of standards, recommendations and technical specifications. Most of these new standards rely on the Spanning Tree Protocols (STP) that we overview in the next subsection.

2.2 Spanning Tree Protocols

The Spanning Tree Protocol (STP), initially proposed in the IEEE 802.1D Standard [3], is responsible for building a loop-free logical topology (a spanning tree topology) over the physical one using a shortest path approach and ensuring connectivity among all nodes, as shown in Figure 1.

The construction of a Spanning Tree (SP) proceeds as follows. First a root bridge is elected (usually the one with the smallest bridge ID is chosen). Then each switch (except for the root one) selects the port which has the smallest distance (according to a given metric) from the root as a root port. Finally all bridges mark as designated ports all the ports connected to a root port of another switch. The other ports, which are neither root nor designated ones, will be considered as blocked ports.

Since STP prevents the creation of loops in the network by blocking redundant links that are not part of the selected tree, the load is concentrated on a single path with no load balancing mechanism. Only in case of failures the blocked links are activated, providing a self-healing restoration mechanism. Thus, the STP suffers of load balancing problems, since it is not possible to activate blocked links during normal conditions.

All network topology changes, including failures, need a recalculation of a new Spanning Tree to reacquire global connectivity. This reconfiguration requires up to 50 seconds and, thus, affects network performance, resulting in poor resiliency. Another negative aspect of the STP is its lack of service guaranties, admission control on traffic policing and shaping, which would allow the support of QoS functionality.

To achieve faster convergence, the Rapid Spanning Tree Protocol (RSTP) IEEE 802.1w [4] was introduced. It is an evolution from the STP that uses a negotiation mechanism to repair the connectivity in case of failures in order to accelerate the convergence to a new Spanning Tree. This way, the RSTP is able to reduce the convergence time by 1 to 3 seconds.

In order to achieve a better utilization of the network with a reduced complexity, the IEEE 802.1s working group introduced the Multiple Spanning Tree Protocol (MSTP) [5], that allows a switch to participate in Multiple Spanning Trees, one tree for each group of VLANs, as those shown in Figure 2.

The existence of multiple overlapped tree instances provides a flexible way of implementing traffic engineering. Firstly, it allows better network resilience, since a link failure does not affect demands assigned to Spanning Trees that do not use it. Secondly, it implies lower network link loads, which makes it possible to maximize the robustness in the event of unpre-

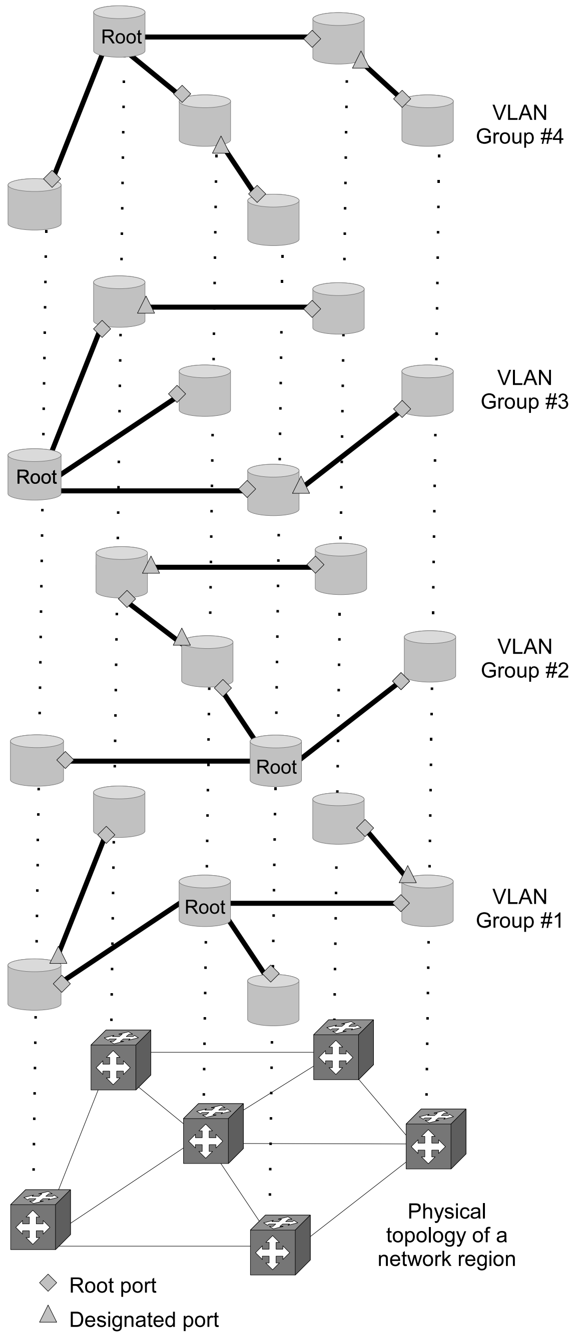


Figure 2: Multiple tree instances in a network region.

dicted demand growth and to minimize service disruptions.

Note that the 802.1s specification does not provide any criteria for the generation of Spanning Trees or their mapping unto VLANs, despite the fact that this point is crucial for the good performance of the MSTP. Therefore, traffic engineering of Ethernet using Multiple Spanning Trees is a widely researched topic; related articles will be reviewed in the next section.

3 Related work

There have been several proposals to reduce energy consumption in Ethernet and Internet related networks. In [21] and [22], it was proposed to adaptively vary the link rate in order to match the offered load. This technique, called Adaptive Link Rate (ALR), aims at ensuring that the energy use over a link is proportional to the link utilization, introducing energy efficiency enhancements to the existing Ethernet. This is also what the Energy Efficient Ethernet (EEE) seeks to obtain with its 802.3az task force [6] that focuses on the introduction of a low power "sleep" mode for idle links intervals in order to obtain energy savings [31].

Implementing energy savings for routers is much more complex, because they often exchange routing information through routing protocols, thus, they cannot stand idle even if there is no data traffic. In addition, if a router enters a sleep mode, it makes itself inactive and unresponsive to what happens in the network, threatening to cause the virtual disconnection of the topology. In this regard, [24] proposes a protocol that coordinates how routers go into power saving mode without degrading quality of service nor network connectivity.

The problem of how to use the IEEE 802.1s Multiple Spanning Tree Protocol to enhance traffic engineering capabilities of Ethernet networks has been addressed by many authors. Traffic flows are defined on a per VLAN basis (the simplest VLAN that can be considered is an E-Line VLAN [19], i.e., a point-to-point VLAN which carries a single commodity) and routing of the traffic flows is done through the network based on Spanning Trees (STs), so that when a VLAN is assigned to a ST Instance (STI), its traffic flow is routed between its end nodes through the unique path defined by the assigned STI.

In [16] the single region MSTP case was considered as well as a resolution technique to determine the MSTP parameters configuration that minimizes the impact of network failures and optimizes load balancing. The objective is achieved minimizing the Worst case Link Load (WLL), which makes the network vulnerable to unpredictable traffic growth. Among all such solutions, the second Worst case Link Load is minimized, and then the third, and so on.

In [32] other objectives are introduced in order to obtain load balancing. For instance average link load minimization given a Worst case Link Load, or worst case link load minimization with a guaranteed average link load. Since the solution of such models can be computationally expensive, heuristics are also proposed.

In [12] the authors claim the importance of an opportune cost metric in the tree construction algorithm. It is shown that the use of a dynamic link cost function provides much higher network utilization than in the case when the link cost is constant. In order to achieve a good load balance and decrease the average delay of the network, a configurable link cost metric for the tree construction algorithm, which is a function of both current link load and link delay, is proposed.

In [26] the authors use a link cost metric which is only a function of the link load, while in [30] the proposed link cost function depends on the delay and on the available bandwidth of the links.

In [27], two algorithms are introduced: MSTGA (Multiple Spanning Tree Generation Algorithm) and VSTMA (VLAN Spanning Tree Mapping Algorithm). The MSTGA generates the Spanning Trees that have the smallest number of links in common, so as to obtain a set of disjoint trees. It has been shown that edge disjoint trees yield near optimal bandwidth allocation and network performance while maintaining resilience to failures. The VLANs are also grouped so that similar VLANs belong to the same group. This way each group will be assigned to one Spanning Tree Instance, the one that minimizes the number of transit nodes, obtaining an optimal mapping in terms of bandwidth usage. The VSTMA performs a good Spanning Tree mapping but this solution does not take into account the load balancing problem.

The same author, in [28] shows how their solution named SSTB, based on the previous algorithms, is able to leverage the network and minimizes bandwidth consumption.

The approach presented in [29], named BMST (Best Multiple Spanning Tree), improves the previous algorithm. It finds the best set of edge disjoint spanning trees based on the shortest path selection and on links/switches load balancing, achieved minimizing the difference between each link/switch load and the mean load among all links/switch. Even if the algorithm can find the best answer for small networks, its complexity is too large for large scale networks.

Finally in [17] a modified version of the MSTP is presented, in which each node has its own Shortest Path Tree. This solution does not seem to be able to perform well in a sparse topology. However, the MSTP is the best choice for better connected topologies because it is more likely that a safe alternate path (to be activated in case of failure) exists.

Differently from the above mentioned approaches, this article deals with the problem of how to use the IEEE 802.1s Multiple Spanning Tree Protocol to minimize energy consumption while guaranteeing QoS. This can be done by finding the best subset of Spanning Trees and the best mapping of the traffic demands to them while minimizing energy consumption. In other words, we specifically exploit the energy efficient structure of Spanning Trees for an energy efficient management and traffic engineering. To the best of our knowledge, this is the first time that such an energy-efficient approach is used in Carrier Ethernet and on networks dealing with Spanning Tree routing. The next Section is devoted to the energy management framework.

4 The modelling framework

Consider an Ethernet Carrier network composed of switches connected through point-to-point links. The network could be represented by a graph consisting of nodes and edges. Since Ethernet uses full-duplex links, traffic in both directions must be considered separately. For this reason, edges must be distinguished from arcs, where an arc is equivalent to a directed edge. We assume that the edge full-duplex capacity and energy consumption are known and so is the energy consumption of the nodes. The network supports a set of VLANs, each of which carries a single commodity characterized by its origin node, its destination node and its traffic demand.

The traffic flows are routed on the network over paths defined by the Spanning Trees the VLANs have been assigned to. Assigning a VLAN to a Spanning Tree means determining the route that should be taken by the traffic of that VLAN. Assigning it to a different Spanning Tree means to route it over a different path. An example is given in Figure 3. Note that the links that do not carry traffic (even the ones belonging to the Spanning Tree matched with the considered VLAN) can be switched off. This is precisely the seed idea behind the modelling framework that aims at finding the best Spanning Trees among a given set and map them to the VLANs minimizing the energy spent by the network itself. This leads to the use of the fewest possible number of nodes and arcs while satisfying the demand. For example, suppose that the links in bold in the network of Figure 4 are the ones through which the traffic is already routed and that a new traffic VLAN must be established between nodes S and D. If the objective is to minimize energy consumption, the VLAN should be mapped unto a Spanning Tree that uses links that are already employed in the network, thus, in this case, it should avoid nodes A, B and C.

In what follows we first present an energy management model without traffic engineering concerns. Later, we review and adapt some load sharing methods developed in the literature and integrate them into the general framework that makes a trade-off between energy management and load sharing. But first, in subsection 4.1 we present a formal notational description of common parameters and decision variables.

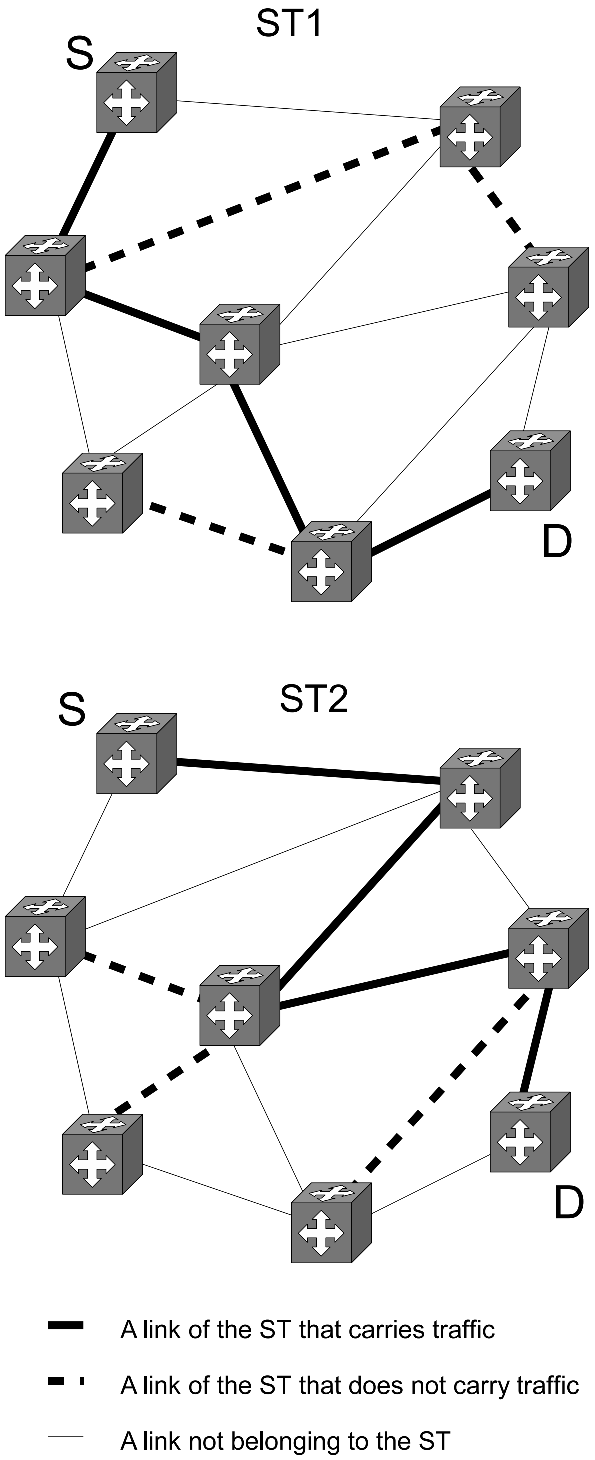


Figure 3: A VLAN carrying a commodity with source node S and destination node D matched with two different Spanning Tree results in two different paths between source and destination.

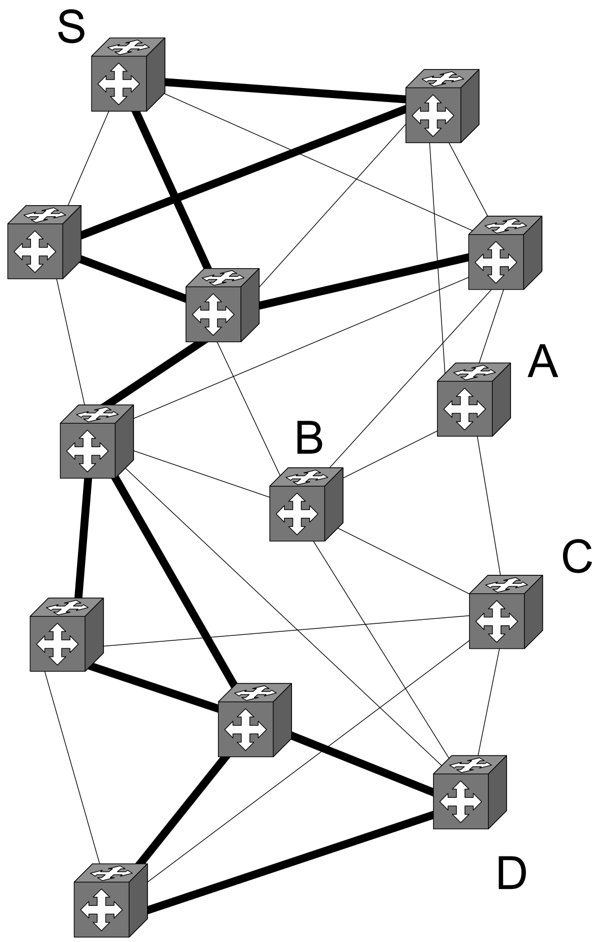


Figure 4: Network example.

4.1 Notational description

Parameters

N	the set of nodes representing the switches of the network.
E	the set of edges representing undirected link between two nodes.
$G(N,E)$	the network graph.
A	the set of arcs, which are directed links between nodes.
Q	the set of VLANs to be routed.
S	the set of Spanning Trees.
$o_q \in N$	the origin node of VLAN $q \in Q$.
$b_q \in N$	the destination node of VLAN $q \in Q$.
$d^q \in \mathbb{R}^+$	the traffic demand of VLAN $q \in Q$.
$c_{\{ij\}} \in \mathbb{R}^+$	the full-duplex capacity of edge $\{i,j\} \in E$.
$\varepsilon_{\{ij\}} \in \mathbb{R}^+$	the energy consumption of edge $\{i,j\} \in E$.
$\varepsilon_i \in \mathbb{R}^+$	the energy consumption of node $i \in N$.
$K \in \mathbb{N}$	the maximum number of Spanning Trees that can be considered. This restriction exists for technical scalability issues.

$$a_{ij}^{sq} = \begin{cases} 1 & \text{if arc } (i,j) \in A \text{ is in the path of the Spanning Tree } s \in S \text{ for VLAN } q \in Q. \\ 0 & \text{otherwise.} \end{cases}$$

Decision variables
The problem of limiting the energy consumption of the network routing the VLAN through the best Spanning Trees while continuing to ensure full connectivity and the management of all requests can be formulated using four decision variables.

The first variables state which STs have been chosen in the solution among the set S:

$$\lambda_s = \begin{cases} 1 & \text{if Spanning Tree } s \in S \text{ is chosen in the solution.} \\ 0 & \text{otherwise.} \end{cases}$$

The mapping between VLANs and STs is defined by the second binary variables:

$$\phi_s^q = \begin{cases} 1 & \text{if VLAN } q \in Q \text{ is assigned to Spanning Tree } s \in S. \\ 0 & \text{otherwise.} \end{cases}$$

Finally, the last two groups of variables are those that determine whether a node or an edge respectively are switched on or not:

$$x_{\{ij\}} = \begin{cases} 1 & \text{if edge } \{i,j\} \in E \text{ is switched on.} \\ 0 & \text{otherwise.} \end{cases}$$

$$y_i = \begin{cases} 1 & \text{if node } i \in N \text{ is switched on.} \\ 0 & \text{otherwise.} \end{cases}$$

4.2 Model P_1

Having defined all the parameters and decision variables, the pure energy consumption model can be defined as follows.

Objective function

$$\min z_1 = \sum_{i \in N} y_i \varepsilon_i + \sum_{\{i,j\} \in A} x_{\{ij\}} \varepsilon_{\{ij\}} + \\ +\beta \left\{ \sum_{i \in N} (1-y_i)\varepsilon_i + \sum_{\{i,j\} \in A} (1 - x_{\{ij\}})\varepsilon_{\{ij\}} \right\} \quad (1)$$

Note that objective function z_1 is composed of two parts: the energy consumption of the “on" nodes and edges and the consumption of the elements in sleep mode. The later is weighted by the parameter β, that is set to 10% according to Energy Efficient Ethernet (EEE) estimates. We make the assumption that the percentage of energy consumption in sleep mode is the same for nodes and edges.

Constraints

$$\sum_{s\in S}\sum_{q\in Q} a_{ij}^{sq}\phi_s^q d^q \leq c_{\{ij\}}x_{\{ij\}} \qquad \forall (i,j)\in A \qquad (2)$$

Constraints (2) are the capacity constraints for each arc (i, j). If the edge $\{i, j\}$ is switched off, no traffic can be routed on it.

$$\phi_s^q \leq \lambda_s \qquad \forall s\in S, q\in Q \qquad (3)$$

Constraints (3) relates the assignment of VLAN q to Spanning Tree s.

$$\sum_{s\in S}\phi_s^q = 1 \qquad \forall q\in Q \qquad (4)$$

Constraints (4) guarantee that each VLAN q is assigned to exactly one Spanning Tree.

$$\sum_{s\in S}\lambda_s \leq K \qquad (5)$$

Constraint (5) guarantees that no more than a fixed number K of trees are in the solution.

$$\sum_{\substack{j\in N:\\(i,j)\in A}} x_{\{ij\}} \leq y_i 2M \qquad \forall i\in N \qquad (6)$$

Where M is a number that has to be greater than K. In fact, if at maximum K different trees can be utilized, not more than $2K$ arcs (both ingoing and outgoing arcs) will be simultaneously activated. Constraints (6) guarantee that a node i can be switched off only if there are no active links incoming or outgoing from that node.

4.3 Revisiting load balancing models

Designing networks based on power consumption only would lead to tree shaped networks with concentrated connections, which are extremely vulnerable to failures. That is why a load balancing objective should also be taken into account.

Considering optimization of load balancing, many different objectives can be set, as it is explained in [32]. One possible objective is to minimize the Worst Link Load (WLL). Having the maximum link load among all links equal to U for a certain link $(i, j) \in A$, with $0 \leq U \leq 1$, implies that the traffic could increase by a factor of $(1-U)/U$ before that link is saturated. This means that the lower the worst utilization value U is, the more robust the network becomes against unpredictable traffic growth. Another possible objective could be to minimize the Average Link Load (ALL), in order to optimize network congestion while exploiting all network resources.

In this article two of the load balancing objectives proposed in [32] have been considered. In the following, we revisit the objectives proposed and adapt the constraints. The idea being to provide the reader with an overall comprehension of flow balancing issues before proposing a final model in section 4.4. For this, we need additional notation and decision variables, given below.

Model parameters

$\mu^* \in [0, 1]$	the maximum utilization value admitted on each arc $(i, j) \in A$.
$\overline{\mu} \in [0, 1]$	the maximum admitted value for the average utilization value over all arcs $(i, j) \in A$.

Decision variables

$u_{ij} \in [0, 1]$	represents the utilization of link (i, j).

The first load balancing objective is the minimization of the Average Link Load with a guaranteed optimal Worst case Link Load. The problem (from now on referred as $P2a$) can be modelled as follows.

Objective function

$$\min z_{2a} = \frac{1}{|A|}\sum_{(i,j)\in A} u_{ij} \qquad (7)$$

where the term z_{2a} is equal to the Average Link Load of the network.

Constraints

$$(3, 4, 5)$$

$$\sum_{s\in S}\sum_{q\in Q} a_{ij}^{sq}\phi_s^q d^q \le c_{\{ij\}}u_{ij} \qquad \forall (i,j) \in A \tag{8}$$

Constraints (8), similarly to constraints (2), are capacity constraints, but unlike them they make explicit the utilization factor for each arc (i, j) employing the variable u instead of the binary variable x.

$$u_{ij} \le \mu^* \qquad \forall (i,j) \in A \tag{9}$$

Contraints (9) limit the utilization value of each link below the threshold of μ^*.

The second load balancing objective is the minimization of the Worst case Link Load with a guaranteed optimal Average Link Load. This problem (from now on referred as $P2b$) can be modelled as follows.

Objective function

$$\min\ z_{2b}^* = \max_{ij} u_{ij} \tag{10}$$

where the term z_{2b}^* is equal to the Worst Link Load of the network.

The minmax function can be modelled as follows:

$$\min\ z_{2b} = \mu \tag{11}$$

$$\text{s.t. } u_{ij} \le \mu \qquad \forall (i,j) \in A \tag{12}$$

$$\mu \in [0, 1]$$

Constraints

$$(3, 4, 5, 8)$$

$$\frac{1}{|A|}\sum_{(i,j)\in A} u_{ij} \le \overline{\mu} \qquad \forall (i,j) \in A \tag{13}$$

Contraints (13) limit the average utilization value over all links below the threshold of $\overline{\mu}$.

4.4 Model P3

Having revisited the issues of load balancing in the previous section, we now integrate them into a framework that aims at the trade-off between load balancing and energy management. For that, some additional notation must be declared.

Model parameters

$\nu^* \in [0, 1]$	the maximum utilization value obtained on each arc $(i, j) \in A$ when the energy objective is solved.
$\overline{\nu} \in [0, 1]$	the average utilization value obtained over all arcs $(i, j) \in A$ when the energy objective is solved.

The first trade-off model (denoted by $P3a$) is the combination between the energy objective (1) of the problem $P1$ and the load balancing objective (7) of the problem $P2a$. It is defined as follows.

Objective function

$$\min\ z_{3a} = \alpha z_1 + (1-\alpha) z_{2a} \tag{14}$$

Parameter α determines how much importance should be given to the energy savings objective .

Constraints

$$(2, 3, 4, 5, 6)$$

$$u_{ij} = \sum_{s\in S}\sum_{q\in Q} a_{ij}^{sq}\phi_s^q d^q / c_{\{ij\}} \qquad \forall (i,j) \in A \tag{15}$$

Contraints (15) are meant to calculate the utilization of each arc (i, j).

$$u_{ij} \le \mu^* + (\nu^* - \mu^*)\alpha \qquad \forall (i,j) \in A \tag{16}$$

Constraints (16) limit the utilization of each link below a threshold that varies between μ^* and ν^* depending on the value assumed by the parameter α.

μ^* is the maximum utilization value admitted on each arc $(i,j) \in A$, while ν^* is the maximum utilization value obtained on each arc $(i,j) \in A$ when the problem $P1$ is solved. So, if $\alpha = 0$ constraints (16) are equivalent to constraints (9), while if $\alpha = 1$ constraints (16) are irrelevant, because all the utilization parameters take on values below ν^*. For intermediate values of α a linear combination between μ^* and ν^* was assumed.

The second trade-off model (denoted by $P3b$) is the combination between the energy objective (1) of the problem $P1$ and the load balancing objective (11) of problem $P2b$. It is defined as follows.

Objective function

$$\min\ z_{3b} = \alpha z_1 + (1-\alpha) z_{2b} \quad (17)$$

Again, parameter α determines how much importance should be given to the energy savings objective and to the load balancing objective.

Constraints

$$(2, 3, 4, 5, 6, 12, 15)$$

$$\frac{1}{|A|} \sum_{(i,j) \in A} u_{ij} \leq \overline{\mu} + (\overline{\nu} - \overline{\mu})\alpha \quad \forall (i,j) \in A \quad (18)$$

Similarly to constraints (16), contraints (18) limit the average utilization value over all links below a threshold that varies between $\overline{\mu}$ and $\overline{\nu}$ depending on the value assumed by the parameter α. $\overline{\mu}$ is the maximum allowed value of the average utilization value over all arcs $(i,j) \in A$, while $\overline{\nu}$ is the average utilization value over all arcs $(i,j) \in A$ obtained when the problem $P1$ is solved. So, if $\alpha = 0$ constraints (18) are equivalent to constraints (13), while if $\alpha = 1$ constraints (18) are irrelevant, because the average utilization values will be equal to $\overline{\nu}$. Again, for intermediate values of α a linear combination between $\overline{\mu}$ and $\overline{\nu}$ was assumed.

5 Experimental approach

5.1 Networks scenarios

The experiments have been carried out considering both realistic and randomly generated networks.

Three realistic network topologies commonly used in the Carrier Grade Ethernet literature were adopted: the *nobel-germany* network used in [9], ii) the *GEANT* network used in [33], and iii) the *USA-24* network used in [10]. Link capacity was equal to 100 Gbps for all the links of the three networks. In each network, the nodes are divided into edge and core nodes by randomly choosing the subset of core nodes, which cannot be neither source nor destination. For what concerns the traffic demands of each different instance, we have first randomly chosen $|Q|$ Origin-Destination pairs between the edge nodes, and then we have assigned to each pair an amount of bandwidth randomly generated in the uniform interval $[0.1Gbps, 10Gbps]$. Note that a dedicated VLAN is assigned to each traffic demand. Since network utilization varies typically from 5% (night hours) to 50% (peak hours) [20] we have scaled the computed demands with a parameter ϖ to obtain three different levels of traffic, with a maximum utilization given by Ψ equal to 50%, 30% and 15%.

The random network topologies were obtained running a C++ instance generator. The program generates a network with a given number of nodes and edges from a full-mesh grid maintaining the edges in the network with a predetermined probability p and discarding the others. All the links capacity have been set to 100 Gbps, while no distinction between edge and core nodes has been made. Traffic demands were generated with the same method adopted for the real network topologies, but without the scaling operation.

We assumed all the networks nodes to be equipped with a Cisco CRS-3 16-Slot Single-Shelf System [1]. This device is compatible with the Cisco CRS-3 1-Port 100 Gigabit Ethernet Interface Modules [2], each of which is responsible for the ingress and the egress packet processing, so that in order to build up a 100 Gbps full-duplex link, we must employ two modules (one at each end). Regarding the energy consumption parameters, they have been estimated from the datasheets of the devices (both nodes and interfaces) mentioned above. The maximum power consumption of a router when chassis is fully configured with line cards and with traffic running is estimated to be 12320 Watts, while the energy consumption of a single line card is 150 Watts (therefore the energy consumption of a full-duplex link is considered to be 300 Watts). Finally, the power consumption in the low-power mode is assumed to be 10% of that in the active mode, in line with the estimates provided by different manufacturers during the standardization process of Energy Efficient Ethernet (EEE) [31].

5.2 Preprocessing

In order to solve our formulations, a set of *Spanning Trees* has to be provided as input. The STs have been calculated using Algorithm A.1, given in the Appendix. Once a valid tree s is computed, it is added to set S, and the binary parameters $T[i,j,s]$ are set equal to 1 when the edge i,j belongs to Spanning Tree s. The data concerning the Spanning Trees is then used through the previously defined binary parameter a_{ij}^{sq} :

$$a_{ij}^{sq} = \begin{cases} 1 & \text{if arc } (i,j) \in A \text{ is in the path} \\ & \text{of the Spanning Tree } s \in S \text{ for} \\ & \text{the VLAN } q \in Q. \\ 0 & \text{otherwise.} \end{cases}$$

The values of a_{ij}^{sq} are calculated solving a flow formulation that allows finding the path that belongs to ST s and that connects the origin and the destination of the demand (VLAN) q. Note that given a Spanning Tree $s \in S$ and a VLAN $q \in Q$, then the path between origin node o_q and destination node b_q is unique in s and the values of parameter a_{ij}^{sq} are uniquely determined. a_{ij}^{sq} must satisfy the following constraints:

$$\sum_{(i,j)\in A:T[i,j,s]=1} a_{ij}^{sq} + \\ - \sum_{(k,i)\in A:T[k,i,s]=1} a_{ij}^{sq} = \begin{cases} 1 & \text{if } i = o_q \\ -1 & \text{if } i = b_q \\ 0 & \text{otherwise} \end{cases} \\ \forall i \in N, \forall q \in Q, \forall s \in S \qquad (19)$$

that represent the well known flow conservation constraints where the flow of each demand q can be routed only through the arcs that belong to tree s. Finally, two other input parameters have to be calculated before solving the formulations. First we have to compute μ^*, the maximum utilization value admitted on each arc $(i,j) \in A$. According to [32], its value is obtained by solving the Worst Link Load (WLL) subproblem:

$$\begin{aligned} & \min \mu \\ & \text{s.t.} \\ & \sum_{s\in S}\sum_{q\in Q} a_{ij}^{sq}\phi_s^q d^q \le c_{\{ij\}} u_{ij} && \forall (i,j) \in A \\ & \phi_s^q \le \lambda_s && \forall s \in S, q \in Q \\ & \sum_{s\in S} \phi_s^q = 1 && \forall q \in Q \\ & \sum_{s\in S} \lambda_s \le K \\ & u_{ij} \le \mu && \forall (i,j) \in A \\ & \mu \in [0,1] \end{aligned}$$

and then equalling μ^* to μ.

Similarly $\overline{\mu}$, which represents the maximum admitted value for the average utilization value over all arcs $(i,j) \in A$, can be obtained by solving the Average

Tests					$\Psi = 15\%$				$\Psi = 30\%$				$\Psi = 50\%$			
ID	Net	$\|N\|$-$\|N_c\|$	$\|E\|$	$\|Q\|$	E_c	N_{on}	E_{on}	$t(s)$	E_c	N_{on}	E_{on}	$t(s)$	E_c	N_{on}	E_{on}	$t(s)$
1	nb-ge	17-7	26	10	59.2	8.4	9.5	0.09	59.9	8.6	9.6	0.12	60.6	9.0	9.7	0.19
2	nb-ge	17-7	26	15	62.3	9.0	10.1	0.29	61.6	8.9	9.9	0.13	64.9	10.2	10.5	1.09
3	nb-ge	17-7	26	20	62.0	9.0	10.0	0.36	62.3	9.1	10.1	0.21	66.7	10.9	10.9	2.32
4	nb-ge	17-7	26	25	62.3	9.1	10.1	0.80	63.0	9.2	10.2	0.64	66.2	10.4	10.8	2.49
5	nb-ge	17-7	26	30	62.0	9.0	10.0	0.29	62.3	9.1	10.1	0.55	66.6	10.8	10.9	4.09
6	nb-ge	17-7	26	60	62.0	9.1	10.0	1.13	62.3	9.1	10.1	1.66	67.4	11.1	11.0	9.99
7	geant	22-10	36	10	57.3	10.7	11.8	0.30	56.5	10.6	11.6	0.25	56.8	10.9	11.7	0.16
8	geant	22-10	36	15	60.5	11.5	12.6	0.44	60.0	11.5	12.5	0.31	61.6	12.2	12.9	0.83
9	geant	22-10	36	20	61.8	12.0	12.9	0.84	59.4	11.4	12.3	0.51	63.0	13.3	13.2	1.60
10	geant	22-10	36	25	62.4	12.1	13.1	2.18	62.1	12.1	13.0	0.87	62.7	13.1	13.1	2.37
11	geant	22-10	36	30	62.1	12.2	13.0	2.29	62.1	12.3	13.0	1.36	63.6	13.5	13.3	4.00
12	geant	22-10	36	60	62.4	12.1	13.1	3.46	62.2	13.0	13.0	4.24	66.1	14.7	13.9	28.2
13	usa	24-12	43	10	49.2	9.7	10.7	0.50	47.5	9.3	10.3	0.18	47.3	9.4	10.2	0.26
14	usa	24-12	43	15	51.9	10.5	11.5	3.50	51.4	10.4	11.3	1.52	51.5	10.7	11.3	1.64
15	usa	24-12	43	20	53.9	11.0	12.0	8.46	53.4	10.9	11.9	3.00	53.0	11.3	11.7	4.20
16	usa	24-12	43	25	53.6	10.9	11.9	9.68	53.4	10.9	11.9	5.09	53.7	11.9	11.9	11.72
17	usa	24-12	43	30	53.9	11.0	12.0	14.67	53.6	10.9	11.9	7.23	54.0	12.0	12.0	16.06
18	usa	24-12	43	60	53.9	11.0	12.0	28.71	53.9	11.4	12.0	56.79	54.0	12.4	12.0	121.27

Table 1: Computational results obtained by solving the problem P1 for real network topologies.

Link Load (ALL) subproblem:

$$\min \frac{1}{|A|} \sum_{(i,j)\in A} u_{ij}$$

s.t.

$$\sum_{s\in S}\sum_{q\in Q} a_{ij}^{sq}\phi_s^q d^q \le c_{\{ij\}} u_{ij} \qquad \forall (i,j)\in A$$

$$\phi_s^q \le \lambda_s \qquad \forall s\in S, q\in Q$$

$$\sum_{s\in S}\phi_s^q = 1 \qquad \forall q\in Q$$

$$\sum_{s\in S}\lambda_s \le K$$

and then equalling $\overline{\mu}$ to the value of the objective function.

At this point, the trade-off objective functions (14) and (17) are actually written as follow:

$$z_3 = \alpha \frac{z_1}{|A|\varepsilon_{\{ij\}} + |N|\varepsilon_i} + (1-\alpha) z_{2a} \qquad (20)$$

and

$$z_3 = \alpha \frac{z_1}{|A|\varepsilon_{\{ij\}} + |N|\varepsilon_i} + (1-\alpha)\frac{z_{2b}}{10} \qquad (21)$$

where the term in the denominator $|A|\varepsilon_{\{ij\}} + |N|\varepsilon_i$ and 10 are normalization terms for z_1 and z_{2b} respectively, which otherwise would take much larger values than z_{2a}, making it difficult to manage the trade-off in relation to the parameter α.

5.3 Computational Results

We now report on results obtained with both the real and the random network topologies.

5.3.1 contains the results obtained for the energy efficiency problem formulation, $P1$. In 5.3.2 we analyze the case of the trade-off framework, while in 5.3.3 a detailed comparison is explored between all the considered models for a trade-off value of $\alpha = 0.2$. Finally we specifically analyze in 5.3.4 the network congestion levels obtained with the different models. Note that for all the tests, a CPLEX time limit of 1000 seconds has been imposed.

5.3.1 Results for Problem P1

Only the results obtained with real network topologies are presented. The results on energy model $P1$ for different levels of traffic load and different numbers of traffic demands $|Q|$ (VLANs) are reported in

Table 1. The Table can be read as follows: first, columns $|N|$-$|N_c|$, $|A|$ and $|Q|$ represent the number of nodes and core nodes, links and traffic demands, respectively. In the following group, $\%E_c$ is the percentage energy consumption normalized with respect to the consumption of the fully powered on network, N_{on} is the number of active nodes and E_{on} is the number of active edges, and $t(s)$ represents the computational time in seconds. All the experiences have been carried out considering $K = 5$ (maximum number of Spanning Trees (ST) that can be simultaneously used) and $|S| = 30$ (cardinality of the input set of STs that can be chosen). All the reported values have been obtained by averaging over 15 different instances.

When the lowest traffic levels are considered (maximum utilization with full active network Ψ equal to 15%) the conditions are comparable with those of the nightly hours and energy savings around 40% for *nobel-germany* and *geant* networks, and around 50% for the *usa* are achieved. The higher energy savings obtained for the *usa* network are explained by the substantially higher connectivity degree (implying higher resource over provisioning) that characterizes the network. It is interesting to note that when peak traffic levels are taken into account (maximum utilization with full active network Ψ equal to 50%), we are still able to reduce the consumption to about 35% in the *nobel-germany* network, 38% in the *geant* network, and 47% in the *usa* network. The considerable amount of energy savings achieved during peak traffic conditions can be motivated by the fact that with model $P1$ we are considering a maximum utilization limit of 100%, and thus the network performance could be affected by a substantial degradation. As expected, for all three networks there is a saving decrease when the number of traffic demands (VLANs) is raised. The opposite behaviour characterizes instead the computational time, that naturally increases when higher number of demands are considered, never,however, exceeding 2 minutes (test 18).

In a second set of experiments, we solved different instances of problem $P1$ with the *geant* network while varying the maximum number K of STs that can be used. The results reported in Table 2 show that the choice of $K = 5$ may represent the good trade-off between energy savings and problem complexity: in fact, only negligible additional energy savings have been achieved with the highest values of K (see columns $K = 10$ and $K = 15$ in Table 2 for tests 12). Note that in Table 2 we report the absolute values of energy saved for only the reference case with $K = 5$, while for all the other instances (different values of K) we report the differential values w.r.t. to the reference ones ($K = 5$).

Differential savings (in Watts)							
Tests			$\Psi = 50\%$				
ID	Net	|Q|	$K = 2$	$K = 3$	$K = 5$	$K = 10$	$K = 15$
7	geant	10	-3769,2	0	131873,6	0	0
8	geant	15	-6222,0	-18	138726,8	0	0
9	geant	20	-12372,0	-54	144353,6	0	0
10	geant	25	-14968,8	-144	148050,8	0	0
11	geant	30	-16844,4	-721,2	149367,2	36	36
12	geant	60	-13868,4	-793,2	151964,0	667,2	667,2

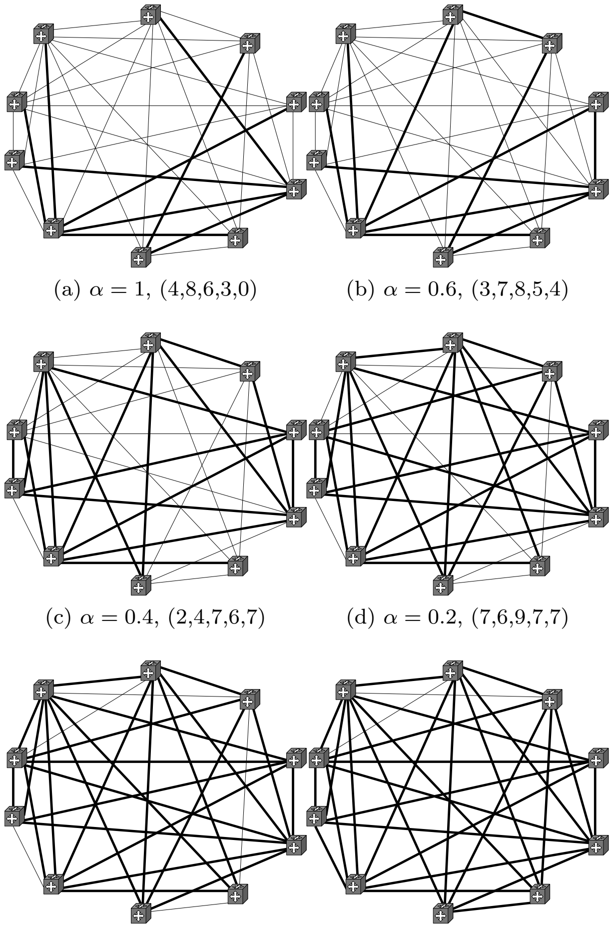
Table 2: Differential energy savings for the geant network while varying the maximum number of Spanning Trees that can be simultaneously used. Differentials have been taken with respect to the case of $K = 5$.

For a more detailed analysis on the number of trees used in the optimal solution by the different formulations, we refer the reader to Table 4 in the next subsection.

5.3.2 Trade-off results

We now discuss the results for the trade-off problems where energy as well as load balancing objectives are accounted for. First of all, to analyze the structure of the computed solutions, we present in Figures 5 and 6 the reduced topologies and the tree structures of the solutions obtained by solving problem $P3a$ (Energy and ALL minimization with WLL constraints) with randomly generated networks of 10 nodes, 31 edges, and 60 demands (VLANs) and different values of trade-off parameter α.

The links on which traffic is routed are in bold. The numbers in parentheses in the caption indicate how many edges of each of the five chosen Spanning Trees are used to route traffic. For example, in Fig-



(a) $\alpha = 1$, (4,8,6,3,0) (b) $\alpha = 0.6$, (3,7,8,5,4)

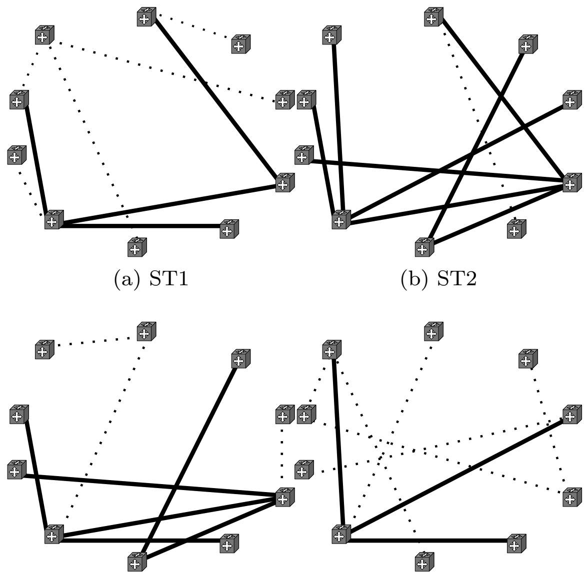
(c) $\alpha = 0.4$, (2,4,7,6,7) (d) $\alpha = 0.2$, (7,6,9,7,7)

(e) $\alpha = 0.1$, (4,7,8,7,8) (f) $\alpha = 0$, (8,7,7,9,8)

Figure 5: The networks obtained considering the load balance problem $P2a$ while minimizing the energy consumption varying parameter α.

ure 5a, 4 edges belonging to the first Spanning Tree carry traffic, while in the second Spanning Tree they are 8, and so on. As it can be seen, if only the energy consumption objective is considered, the portion of the network that is employed to route traffic is reduced to a tree. The more the load balancing objective is taken into account, the more the number of used edges increases.

In Figure 6 we illustrate in more detail the results concerning the network of Figure 5a, the one that considers only the energy consumption objective.



(a) ST1 (b) ST2

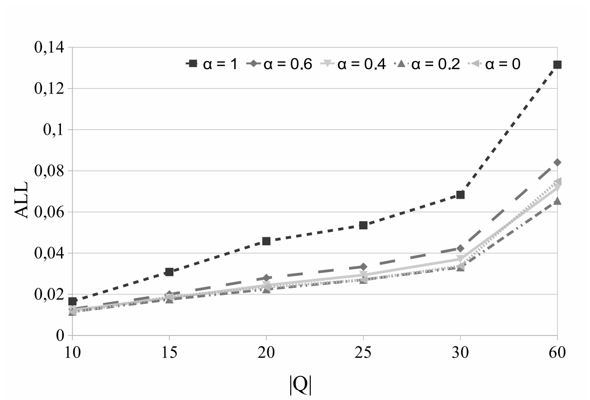
(c) ST3 (d) ST4

Figure 6: Active edges in the Spanning Tree Instances chosen for the network of Figure 5a.

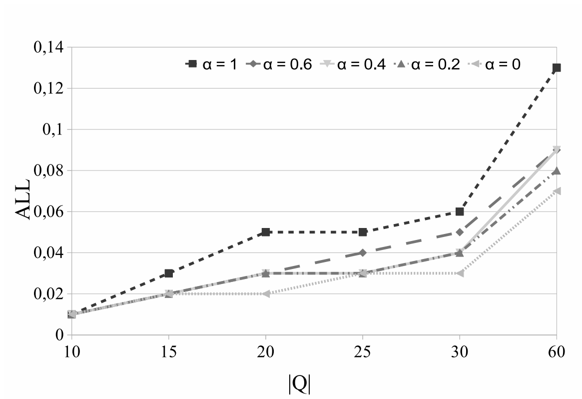
The figure shows the Spanning Tree Instances chosen for the network. The edges being used to route the commodities in each Spanning Tree are highlighted in bold. In the first ST, 4 edges are active, 8 in the second, 6 in the third and 3 in the fourth. The fifth tree is not reported because only four trees were activated in the final solution.

Moreover, we report in Figures 7a, 7b and 7c a summary of the values of average link load (ALL), worst link load (WLL) and energy savings, respectively, averaged over 15 different random network instances with the same topology of Figure 5 and different random traffic matrices, obtained by solving model $P3a$ (objective (14)) with different values of α and for different number of traffic demands ($|Q|$ parameter).

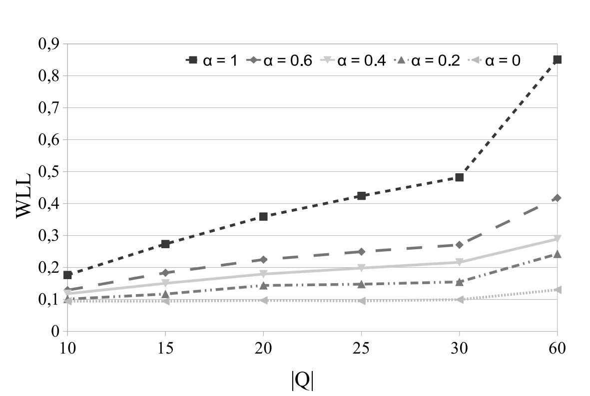
Similarly, Figure 8a, Figure 8b and Figure 8c summarize the same values when problem $P3b$ (objective (17)), energy and WLL minimization with ALL



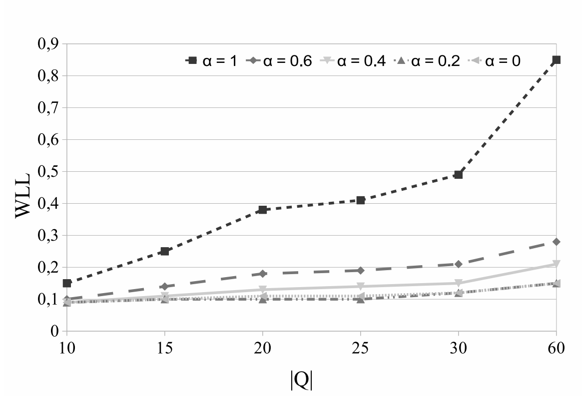
(a) ALL *P3a*



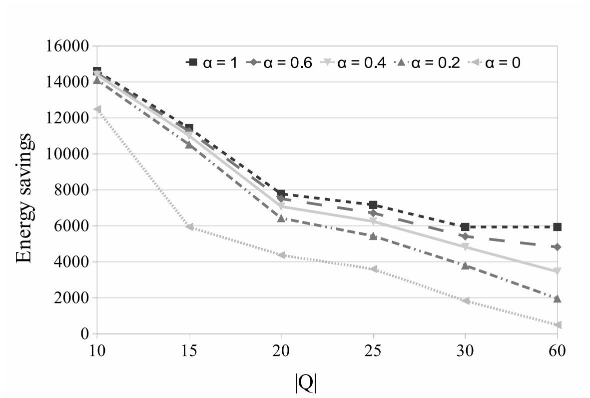
(a) ALL *P3b*



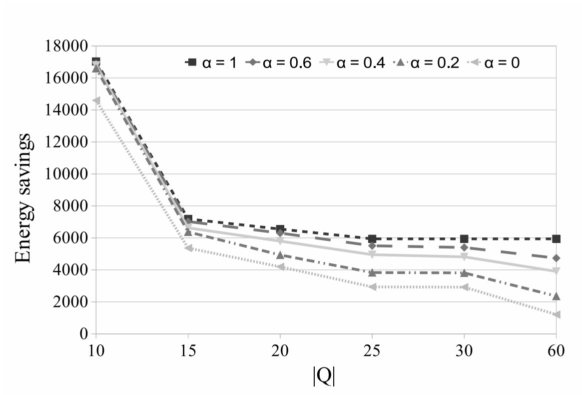
(b) WLL *P3a*



(b) WLL *P3b*



(c) Savings *P3a*



(c) Savings *P3b*

Figure 7: Results obtained for different values of α when solving problem $P3a$.

Figure 8: Results obtained for different values of α when solving problem $P3b$.

constraints) is considered. All the graphs show that both trade-off models behave similarly, regardless of the load balancing function. Both average link load, worst link load and energy savings decrease when the trade-off is shifted toward the load balancing objective. As for ALL and WLL, the greater reductions are registered when passing from $\alpha = 1$ to $\alpha = 0.6$. Thus a 40% weight assigned to the load balancing objective allows to compute solutions with acceptable congestion. On the other hand, the energy saving remains remarkable even when the highest priority is assigned to the load balancing objectives (see $\alpha = 0.2$ curves). Thus, load balancing objectives and constraints are very useful because they lead the classic $P1$ formulations toward less congested solutions, without excessively decreasing the energy savings. Note that in many cases it is also possible to save energy when $\alpha = 0$. This surprising fact can be explained as follows: even though in this case energy consumption is no longer part of the objective function, both models $P3a$ (Energy and ALL minimization with WLL constraints) and $P3b$ (Energy and WLL minimization with ALL constraints) continue to take into account the switching off variables. Thus, if the switching-off of an element does not negatively impact load balancing, there is a possibility that the solver computes a final solution where the element itself is considered off. Moreover, the curves show that the increase of the number of demands has a strong negative impact on energy savings (see for example the large drop in Figure 8c when passing from $|Q| = 10$ to $|Q| = 15$). This is due to the fact that with the random generated instances, all the network nodes could be source or destination of traffic and given that a source/destination cannot be switched-off, a higher number of demands leads to a higher number of nodes that have to be maintained on.

Similar results have been obtained with the real network topologies. A summary is reported in Table 3, where the values of energy consumption (E_c), average link load (ALL) and worst link load (WLL) obtained for models $P3a$ and $P3b$ and different values of α (trade-off parameter) are portrayed. Note that all traffic matrices were generated for peak traffic levels ($\Psi = 0.5$). For both models $P3a$ (Energy and ALL minimization with WLL constraints) and $P3b$ (Energy and WLL minimization with ALL constraints) it is interesting to make a comparison between the value obtained with $\alpha = 1$ and $\alpha = 0.2$. As for model $P3a$, when *nobel-germany* and *geant* networks are considered (tests 1-2-3-4-5-6-7-8-9-10-11-12), we have registered an average energy saving reduction of 10% when passing from $\alpha = 1$ to $\alpha = 0.2$. On the other hand, the greater weight assigned to the load balancing objective, leads to a decrease of the max utilization level in the order of 40% (from 95% to 55%). As for the average link load, no remarkable differences between the different tests are registered. The results obtained by considering the *usa* network follows the same trend, but with smaller variations of energy consumption and WLL when the trade-off parameter is varied.

In what concerns $P3b$, a significant smaller reduction (w.r.t. to model $P3a$) of both energy savings and max utilization level is obtained when varying the trade-off parameter. The difference between the values obtained with $\alpha = 0.2$ and $\alpha = 1$ is around 2% for the energy savings, and around 20% for the max utilization. Model $P3a$ is thus more conservative than $P3b$ in what concerns the load balancing, while $P3b$ gives more priority to energy consumption reduction. In other words, for the same α parameter, model $P3a$ obtains energy consumption up to 10% higher than model $P3b$ for the same instance, with however a max utilization level about 15% smaller. Moreover, the behaviours of both the models $P3a$ and $P3b$ become more similar when high connected networks (as the *usa* network) are handled.

5.3.3 Detailed comparative results

In this section the energy consumption problem $P1$ and the two trade-off problems $P3a$ and $P3b$ are exhaustively analyzed. For this set of tests we considered all the three real network topologies. Problems $P3a$ (Energy and ALL minimization with WLL constraints) and $P3b$ (Energy and WLL minimization with ALL constraints) have been solved with the trade-off parameter α fixed to $= 0.2$, and the traffic matrices have been generated by using $\Psi = 0.5$. Again, all the results represent mean values over 15 instances.

Tests		$\alpha = 0$			$\alpha = 0.2$			$\alpha = 0.4$			$\alpha = 0.6$			$\alpha = 1$		
ID	Net	E_c	ALL	WLL	E_c	ALL	WLL	E_c	ALL	WLL	E_c	ALL	WLL	E_c	ALL	WLL
P3a																
1	nb-ge	79.1	15.0	49.8	71.7	14.7	53.8	67.3	14.0	60.8	65.8	14.1	65.5	61.0	14.7	87.2
2	nb-ge	83.7	17.3	49.7	75.5	16.8	56.6	70.5	16.5	62.8	67.6	16.3	70.7	64.9	18.4	92.9
3	nb-ge	87.4	20.7	50.5	74.5	19.3	57.1	72.3	18.8	67.0	67.7	18.5	74.4	66.7	21.3	92.1
4	nb-ge	86.8	19.8	50.0	77.4	18.9	57.7	74.0	18.5	65.7	68.8	18.3	73.2	66.2	20.4	93.5
5	nb-ge	87.5	21.7	49.7	77.1	20.4	58.0	71.7	19.8	66.6	68.0	19.7	72.8	66.6	22.7	91.8
6	nb-ge	89.4	25.8	49.5	80.1	24.7	59.0	75.1	23.8	68.6	67.8	23.5	77.1	67.4	26.3	95.2
7	geant	71.4	9.3	49.7	63.7	9.4	53.3	62.0	9.4	58.1	60.4	9.5	64.1	56.8	9.4	84.2
8	geant	79.6	12.8	49.8	70.6	12.9	55.5	67.0	12.6	63.1	65.5	12.4	69.4	61.6	13.5	91.0
9	geant	83.5	16.5	49.8	76.0	16.1	56.6	73.1	15.5	63.6	68.6	15.2	72.4	63.0	16.3	91.2
10	geant	86.2	16.7	49.7	72.4	15.9	57.8	70.4	15.6	66.1	66.8	15.6	74.7	62.7	17.3	95.5
11	geant	89.6	19.1	50.0	77.6	18.3	58.1	72.4	17.8	66.3	69.0	17.6	74.3	63.6	19.5	95.2
12	geant	93.0	25.8	49.9	81.4	24.4	59.2	76.3	24.0	69.0	72.1	23.8	78.5	66.1	26.3	99.1
13	usa	52.8	6.5	53.3	49.8	6.5	53.3	49.3	6.6	58.4	48.7	6.7	64.0	47.3	7.7	85.9
14	usa	56.3	9.9	49.8	53.2	9.2	56.5	52.6	9.0	62.4	52.3	9.0	70.6	51.5	11.0	91.0
15	usa	58.7	11.5	49.8	55.2	10.6	56.5	54.4	10.3	63.4	54.1	10.3	71.8	53.0	12.5	92.1
16	usa	58.7	13.0	49.9	54.3	11.4	57.8	54.3	11.2	64.5	54.1	11.0	74.4	53.7	14.2	95.0
17	usa	64.3	15.2	49.8	55.2	12.6	57.8	54.5	12.2	66.1	54.4	12.2	75.4	54.0	15.6	94.6
18	usa	61.8	16.4	51.0	54.8	15.2	59.2	54.7	15.0	67.6	54.6	15.1	75.0	54.0	19.0	98.4
P3b																
1	nb-ge	69.7	12.6	66.9	66.5	12.7	68.0	64.7	13.0	74.1	64.3	13.2	74.2	64.1	13.8	86.3
2	nb-ge	74.0	15.7	72.8	69.3	16.0	71.7	66.5	16.4	77.4	66.5	16.4	77.1	66.3	17.1	92.7
3	nb-ge	74.5	17.2	71.4	68.4	17.6	70.3	67.0	18.0	73.7	66.5	18.2	75.3	66.3	18.8	94.5
4	nb-ge	74.2	18.9	70.5	68.9	19.3	68.9	67.4	19.6	72.5	67.3	19.8	71.9	67.0	20.7	93.9
5	nb-ge	77.3	20.7	70.1	68.5	21.2	70.7	68.1	21.5	70.0	67.7	21.9	72.5	67.4	22.5	96.4
6	nb-ge	75.8	23.9	71.9	67.9	24.5	72.3	67.8	25.1	72.3	67.7	25.7	73.3	67.4	26.1	95.6
7	geant	61.0	7.6	68.0	59.6	7.6	67.5	57.9	7.7	72.6	57.6	7.9	74.5	57.0	8.3	82.9
8	geant	68.9	12.6	71.5	65.1	12.9	71.8	63.1	13.0	77.4	62.8	13.3	79.3	62.4	13.6	91.0
9	geant	72.0	15.1	77.6	68.7	15.3	74.4	64.8	15.6	83.2	64.6	15.9	79.2	64.1	16.5	92.6
10	geant	72.9	16.7	79.9	66.2	16.9	80.6	64.3	17.2	83.7	63.4	17.7	86.5	63.3	18.2	95.8
11	geant	75.2	18.4	83.2	67.4	18.8	80.0	64.9	19.2	84.5	64.6	19.7	84.1	63.6	19.5	95.2
12	geant	79.4	24.2	84.1	70.5	24.8	79.5	66.8	25.3	90.8	66.2	25.9	93.7	66.1	26.7	98.1
13	usa	52.0	6.7	60.9	51.0	6.8	56.6	50.4	7.0	56.2	49.9	7.1	59.7	49.5	7.6	89.1
14	usa	54.4	8.8	70.5	53.1	9.2	62.2	52.5	9.6	60.6	52.3	9.9	60.3	51.7	10.4	90.3
15	usa	57.0	10.0	65.9	54.5	10.4	61.6	53.9	10.8	62.6	53.9	11.2	61.1	53.5	11.9	94.3
16	usa	56.4	12.2	70.6	55.4	12.8	60.2	54.3	13.3	58.6	54.3	13.7	57.8	53.8	14.6	96.4
17	usa	56.2	12.4	70.7	55.2	13.1	56.9	54.6	13.7	57.4	54.5	14.2	57.1	54.0	15.3	96.3
18	usa	57.1	14.3	61.6	54.7	15.0	53.1	54.7	15.7	52.1	54.6	16.2	52.4	54.0	17.6	98.4

Table 3: Computational results obtained fr problems P3a and P3b with the real network topologies and traffic matrices generated by using $\Psi = 0.5$.

Results are reported in Table 4. Regarding energy savings, as expected the best results are obtained with problem $P1$. As previously highlighted, $P3a$ generally achieves lower energy savings than $P3b$, while guaranteeing lower utilization levels. There are instead no significant differences for the average link load levels.

It is important to note that with the *nobel-germany* and the *geant* networks, WLL lower levels are not achieved with model $P3b$, that is the model that explicitly minimizes the max utilization level, but rather with model $P3a$. This surprising behaviour is explained by the role played by the network congestion constraints (16) (for problem $P3a$) and (18) (for problem $P3b$). Constraint (16), that limits the WLL allowed, seems in fact to be stricter than constraint (18), that limits the ALL for some networks. An illustrative example is shown in Figure 9. The top figure shows a two-link network with two units of demand and 4 units of capacity. In the first case the WLL and the ALL both equal 50% . When one of the links is put to sleep, the WLL of the network raises to 100% whereas the ALL stays at 50%. This example clearly shows that the WLL grows faster than the ALL. Thus, more elements can be generally switched off when the maximum WLL is simply weighted in the objective function instead of imposed as constraint. One way for the ALL to keep up with the WLL increase would be to increase the hop length of the solution path, which is what happens in more connected networks, such as *usa*.

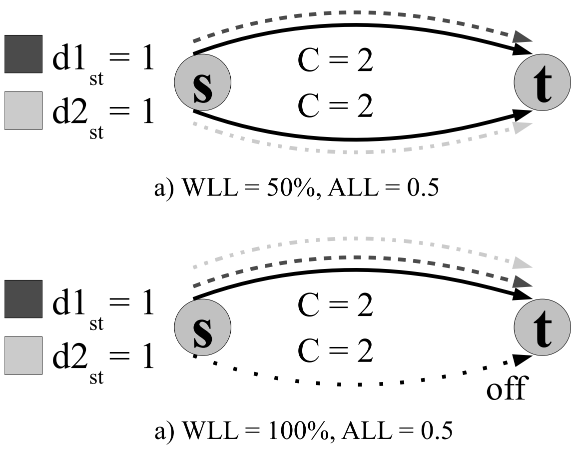


Figure 9: Example concerning ALL and WLL variations when network elements are switched off. Two unitary demands between nodes s and t has to be satisfied, with a link capacity equal to 2 for both links.

Another important feature of the solutions obtained that have to be investigated is the average number of STs utilized in the final solutions (column *tree*). Data suggests that all three models tend to exploit the highest allowed number of trees. That does not mean that it would not be possible to obtain the same objective values by using fewer trees, but simply that it is easier for CPLEX to find optimal solutions where the maximum tree number constraint is tight. As to the computational time, model $P3a$ seems to be clearly the fastest one, while model $P3b$ seems to be the slowest. As expected, the complexity of the problem increases when the number of demands (VLANs) is raised. The 1000 seconds time limit has been reached for some instances with 60 demands (tests 6-12-18). Note that the reported times do not include the computing required to solve the auxiliary problems for the trade-off problem.

5.3.4 Network congestion analysis

Finally, we report in Table 5 some measures of network congestion for the network solutions obtained by solving models $P1$, $P3a$ and $P3b$ ($P3a$ and $P3b$ with $\alpha = 0.2$). In addition, for comparison purposes, we also report the congestion values (column P_{cong}) obtained by solving the load balancing optimization model with fully splittable multicommodity flows proposed in [18]. The congestion levels reported in the table were calculated as:

$$\frac{1}{\sum_{q \in Q} d^q} \sum_{(i,j) \in A} \frac{f_{ij}}{(c_{ij} - f_{ij})} \qquad (22)$$

Where $f_{ij} = \sum_{s \in S} \sum_{q \in Q} a_{ij}^{sq} \phi_s^q d^q$ is the flow on link i, j and c_{ij} is the link capacity. Only active links have been considered.

When the lowest traffic levels are considered ($\Psi = 15\%$), models $P3a$, $P3b$ and P_{cong} obtain similar values of congestion. In this case, model $P1$, that does not consider any particular constraints on network saturation, achieves quite low value of congestion. The situation is completely different when working in peak traffic conditions ($\Psi = 50\%$). In this case, solutions for $P1$ are extremely congested and network performance is significantly deteriorated. Model $P3a$ returns instead solutions with a really small congestion increase w.r.t. to those calculated by the load balancing optimization models (about 10% increase). As for model $P3b$ the situation is quite different, since congestion increases can go beyond 100% of the ideal case (tests 10-11-12). In conclusion, model $P3a$ seems the most suitable to guarantee at the same time both energy savings and network performance.

Tests		$P1$					$P3a$					$P3b$				
ID	Net	E_c	ALL	WLL	$tree$	$t(s)$	E_c	ALL	WLL	$tree$	$t(s)$	E_c	ALL	WLL	$tree$	$t(s)$
1	nb-ge	59.2	15.0	89.3	3.9	0.09	71.7	14.7	53.8	4.8	0.12	66.5	12.7	68.0	4.9	0.35
2	nb-ge	62.3	18.1	94.3	4.3	0.29	75.5	16.8	56.6	4.7	0.45	69.3	16.0	71.7	4.9	4.68
3	nb-ge	62.0	21.3	94.9	4.7	0.36	74.5	19.3	57.1	5.0	0.21	68.4	17.6	70.3	5.0	12.16
4	nb-ge	62.3	20.5	93.8	4.9	0.80	77.4	18.9	57.7	4.9	0.88	68.9	19.3	68.9	5.0	22.41
5	nb-ge	62.0	23.0	95.0	4.9	0.29	77.1	20.4	58.0	5.0	4.30	68.5	21.2	70.7	4.9	71.51
6	nb-ge	62.0	26.2	97.4	5.0	1.13	80.1	24.7	59.0	5.0	317.25	67.9	24.5	72.3	5.0	247.38
7	geant	57.3	9.6	86.7	4.5	0.30	63.7	9.4	53.3	4.5	0.13	59.6	7.6	67.5	4.5	0.21
8	geant	60.5	13.4	91.5	4.9	0.44	70.6	12.9	55.5	4.9	0.16	65.1	12.9	71.8	4.9	1.09
9	geant	61.8	16.6	93.3	4.8	0.84	76.0	16.1	56.6	4.9	0.45	68.7	15.3	74.4	4.9	3.56
10	geant	62.4	16.9	96.3	4.7	2.18	72.4	15.9	57.8	5.0	1.56	66.2	16.9	80.6	4.8	3.80
11	geant	62.1	19.8	97.3	4.9	2.29	77.6	18.3	58.1	5.0	2.39	67.4	18.8	80.0	4.9	81.86
12	geant	62.4	26.0	99.2	4.9	3.46	81.4	24.4	59.2	5.0	152.18	70.5	24.8	79.5	4.9	262.00
13	usa	49.2	8.0	92.6	4.5	0.50	49.8	6.5	53.3	4.6	0.08	51.0	6.8	56.6	4.7	0.48
14	usa	51.9	10.8	93.0	4.5	3.50	53.2	9.2	56.5	4.9	0.21	53.1	9.2	62.2	4.9	1.12
15	usa	53.9	12.4	94.6	4.7	8.46	55.2	10.6	56.5	5.0	0.24	54.5	10.4	61.6	4.9	9.52
16	usa	53.6	14.1	98.1	5.0	9.68	54.3	11.4	57.8	5.0	0.28	55.4	12.8	60.2	5.0	46.98
17	usa	53.9	16.1	96.7	4.9	14.67	55.2	12.6	57.8	5.0	0.61	55.2	13.1	56.9	5.0	48.49
18	usa	53.9	18.8	99.0	5.0	28.71	54.8	15.2	59.2	5.0	2.55	54.7	15.0	53.1	5.0	795.18

Table 4: Computational results obtained for problems $P1$, $P3a$ and $P3b$ with real network topologies and traffic matrices generated by using $\Psi = 0.5$. Problems $P3a$ and $P3b$ have been solved with $\alpha = 0.2$.

Congestion level													
Tests		$\Psi = 15\%$				$\Psi = 30\%$				$\Psi = 50\%$			
ID	Net	$P1$	$P3a$	$P3b$	P_{cong}	$P1$	$P3a$	$P3b$	P_{cong}	$P1$	$P3a$	$P3b$	P_{cong}
7	geant	35.5	30.4	28.7	28.6	89.2	37.8	41.3	36.1	139.6	42.5	44.5	38.0
8	geant	36.7	28.4	27.3	26.7	90.0	35.1	36.9	33.3	353.9	49.2	52.7	43.6
9	geant	46.0	30.7	31.6	30.3	89.4	36.8	39.7	35.7	494.9	48.0	55.4	41.1
10	geant	41.5	31.7	31.3	30.3	64.8	35.2	36.7	32.8	7027.7	49.7	158.0	43.4
11	geant	42.3	31.5	32.7	31.5	275.4	37.0	40.2	35.1	180.7	45.5	103.5	41.2
12	geant	45.5	29.4	31.3	29.7	138.3	36.8	42.4	34.5	308.3	47.7	81.4	43.4

Table 5: Comparison between the different level of congestion obtained by solving the different models. Problems $P3a$ and $P3b$ have been solved with $\alpha = 0.2$. Problem P_{cong} for network congestion minimization is presented in [18].

6 Conclusion

This paper addresses the problem of how to use the IEEE 802.1s Multiple Spanning Tree Protocol to improve energy consumption efficiency of Carrier Ethernet networks.

The proposed approach computes the best subset of Spanning Trees and the best mapping of the traffic demands (VLANs) in order to reduce energy consumption. This is performed in such a way that a portion of the network is forced by the objective function of the model to remain unused, thus making it possible to put in sleep mode the elements of that portion of the network to save energy. This leads to the use of the fewest possible number of nodes and arcs, while continuing to ensure full connectivity and the management of all requests. The proposed approach is particularly efficient in reducing energy consumption when network traffic is low, even if non negligible energy savings can be achieved also with peak traffic when network capacity is over provisioned as in most of operator networks.

We have taken advantage of some load balancing techniques proposed in the literature and adapted two of them to our problem to specifically address the energy reduction goal. Moreover, we have proposed a trade-off modelling framework in which energy consumption and load balancing are considered together in order to avoid affecting quality of service when reducing energy.

The set of experimental results shows that the energy-aware model presents good results in terms of energy consumption, but at the expense of a non negligible QoS degradation (the utilization values of some links reached nearly 0.9 in the worst cases).

On the other hand, the trade-off model is able to balance quite efficiently energy savings and performance, since it achieves very good results in terms of load balancing and network congestion level just by giving up a few percentage points of energy savings.

A Spanning Tree Generation

Algorithm A.1: ST GENERATION(E, N, s)

$Tree \leftarrow \emptyset$
$S \leftarrow \emptyset$
for each $(i, j) \in E$
  do $cost(i, j) \leftarrow Uniform[0, 1]$
while $cont \leq s$
do
  while $card(Tree) < card(N) - 1$
    do
      $BestEdge \leftarrow$ MINCOST(E)
      $E \leftarrow E \backslash BestEdge$
      NOLOOP$(BestEdge)$
  if $(\nexists\, T \in Forest : T = Tree)$ **and** CRITERION$(Tree)$
    then
      $S \leftarrow Forest \cup Tree$
      UPDATE$(cost)$

In order to find the Spanning Trees which are the elements of the set S Kruskal's algorithm has been used. Each Spanning Tree has been generated by assigning random costs to the links with a uniform distribution, so that Kruskal's algorithm could give at each cycle a different Spanning Tree as output.

The function MINCOST(E) provides the minimum cost link in the set E. The procedure NOLOOP$(BestEdge)$ determine if the edge given as input will create a loop and adds it to the set $Tree$ if not. The procedure is defined by the following algorithm:

Algorithm A.2: NOLOOP$(BestEdge)$

if $comp[i] = 0$
then
  if $comp[j] = 0$
    then
      $comp[i] \leftarrow NewComp$
      $comp[j] \leftarrow comp[i]$
      $Tree \leftarrow Tree \cup (i, j)$
    else
      $comp[i] \leftarrow comp[j]$
      $Tree \leftarrow Tree \cup (i, j)$
else
  if $comp[j] = 0$
    then
      $comp[j] \leftarrow comp[i]$
      $Tree \leftarrow Tree \cup (i, j)$
  else if $comp[j] \neq comp[i]$
    then
      for each $n \in N$: $comp[n] = comp[j]$
        do $comp[n] \leftarrow comp[i]$
      $Tree \leftarrow Tree \cup (i, j)$

In Algorithm A.2 variable $comp[i]$ indicate which component of the temporary Tree the node i belongs to. Its default value is zero. Given an Edge (i, j) four cases must be considered:

- neither node i or j belong to the tree ($comp[i] = comp[j] = 0$). In this case the edge (i, j) will not create loops and can be added to the set $Tree$;
- node i (or j) does not belong to the tree, while node j (or i) has already been added to the tree. Again the edge is added without creating loops;
- both nodes i and j already belong to the set $Tree$ but in two disconnected components ($comp[i] \neq comp[j]$). In this case the edge can be added and the two components are merged.
- both nodes i and j already belong to the set $Tree$ in the same connected component ($comp[i] = comp[j] \neq 0$). In this case the edge cannot be added, otherwise it would create a loop.

The function CRITERION$(Tree)$ provides an additional criterion to decide whether to add or not the considered tree to the set S. If not mentioned, it's default value is 1.

Finally, function UPDATE$(cost)$ assigns new costs to the links, according to the uniform distribution. Other ways to generate trees have also been considered. In the first alternative, function CRITERION($Tree$) has been calibrated in such a way that only the trees which involve as few edges as possible could be added to the set S. In this case, the function has been set to 1 only when the number of edges employed to route traffic through the considered tree was below a threshold. Another option concerns the function to update the edge costs. In this case, at the end of each cycle a fixed value is added to the cost of every edge. This value is related to the number of time each edge has been chosen to belong to a tree, in order to discourage the choice of the edges that have been selected more often. This method should generate trees as diverse as possible. However, these alternative tree generator methods do not produce better results than the ones obtained with the basic one.

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Antonio Capone is full professor at the Information and Communication Technology Department of the Politecnico di Milano (technical university), where he is the director of the Advanced Network Technologies Laboratory (ANTLab). Dr. Capone is co-founder and CTO of MobiMESH, a spin-off company of Politecnico di Milano. His expertise is on networking and his main research activities include protocol design (MAC and routing) and performance evaluation of wireless access and multi-hop networks, traffic management and quality of service issues in IP networks, and network planning and optimization. On these topics he has published more than 160 peer-reviewed papers in international journal and conference proceedings. He received the M.S. and Ph.D. degrees in electrical engineering from the Politecnico di Milano in 1994 and 1998, respectively. In 2000 he was visiting professor at UCLA, Computer Science department. He currently serves as editor of ACM/IEEE Trans. on Networking, Wireless Communications and Mobile Computing (Wiley), Computer Networks (Elsevier), and Computer Communications (Elsevier). He was guest editor of a few journal special issues and served in the technical program committee of major international conferences. He is a Senior Member of the IEEE.

Daniele Corti was born in Lecco in 1986. He received the Bachelor Degree in Telecommunications Engineering from Politecnico di Milano (Italy) in 2008, and the Master Degree in Telecommunications Engineering from Politecnico di Milano in 2010. His research interest include topics related to energy-aware network design and traffic engineering (green networking). He has worked for SIAE MICROELETTRONICA since January 2011.

Luca Gianoli was born in Milano in 1986. Currently he is a Ph.D. student at ANTLab (Advanced Network Technologies Laboratory), Politecnico di Milano (Italy), Electronics and Information Department and at École Polytechnique de Montreal, Département de génie électrique. He received the Bachelor Degree in Telecommunications Engineering from Politecnico di Milano (Italy) in 2008, and the Master Degree in Telecommunications Engineering from Politecnico di Milano in 2010. On January 2011 he started his double Ph.D. program in Information Technology at the Electronics and Information Department (DEI) of Politecnico di Milano with Prof. Antonio Capone and at the Département de génie électrique of École Polytechnique de Montreal with Prof. Brunilde Sansó. His research interests include topics related to energy-aware network design and traffic engineering (green networking).

Brunilde Sansó is a full professor of electrical engineering at École Polytechnique de Montreal and director of the LORLAB. Her interests are in performance, reliability, design, and optimization of wireless and wireline networks. She is a recipient of several awards, Associate Editor of Telecommunication Systems, and editor of two books on planning and performance.