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Abstract

The Future Internet demands energy efficient communication to cope with the ever increasing power consumption. Virtualization techniques have proved to be effective in reducing power consumption of network devices. An open issue in virtualization for green networking is the search for an energy-efficient mapping of virtual networks onto physical networks. This paper introduces a new model for the mapping of virtual networks which aims at reducing the energy consumption. This model is based on an integer linear programming formulation and several parameters, corresponding to characteristic of real networks, are considered. Simulation results attest the efficacy of the proposal.

1 Introduction

The minimalist approach and the independence of specific network technology at the link layer have enabled the global spread of the Internet. The core of the Internet was designed to be simple, using the TCP/IP stack operational over different types of link layer technologies. However, as a consequence of this simplicity, various attempts have been made to provide missing features in its original design. The impossibility of including new features in the core of the Internet has prevented the development of several applications and services. This has often been labeled the "ossification of the Internet".

To overcome these limitations, various new architectures and mechanisms have been proposed to promote the evolution of the Internet [2] [3] [4]. Several of these are based on

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network virtualization which allows the definition of virtual networks (VNs) composed of virtual routers and links; these are then hosted by routers and links in real networks called "network substrates". Network virtualization allows the coexistence of different protocol stacks and architectures on the same substrate, without the need of modifying the physical network. Moreover, it imposes no restrictions on these protocols and architectures.

One of the main issues in network virtualization is the efficient mapping of VNs onto the substrate network [5] [3]. This mapping determines the allocation of routers and links of a VN onto the routers and links of the substrate network. However, the search for the optimal mapping of VNs is an NP-hard problem [4].

In recent years, telecommunication companies (telcos) and Internet Service Providers (ISPs) have faced an increase in energy consumption due to the growing spread of broadband access and the expansion of the services offered. According to Bolla et al. [6], the increase in the volume of the network traffic follows Moore's law, doubling every 18 months; while silicon technologies improve their energy efficiency according to Dennard's law, by a factor of 1.65 every 18 months. Thus, there is a constant increase in power consumption related to communication networks, which corresponds to 2% to 10% of the world current power consumption and this is expected to increase in the coming years.

Advances in hardware have allowed the design of energy efficient network devices by the adoption of "power on demand" operation. Techniques employed at the physical layer have made transmission more energy efficient. However, the advancement of the state of the art in energy efficient networking is expected to happen at the architectural level [7]. In this context, network virtualization plays a key role since it can replace a great amount of physical elements. Besides that, protocol processing and virtualized elements can be placed at sites with renewable energy.

This paper introduces an optimization model to map virtual networks onto network substrates with the aim of saving energy. The model considers realistic assumptions of virtual and physical networks. The model also considers the existence of repositories of images of different software and protocol stacks, which are used to instantiate the virtual routers. The proposal is based on a 0–1 integer linear programming (ILP). The objective of the formulation is to minimize the total amount of energy consumption of the virtual networks, and yet guaranteeing the QoS requirements of the virtual networks. The proposed mapping algorithms are intended to be used by admission control agents, which can be either centralized or distributed agents.

This paper is organized as follows: Section II explains the adopted energy consumption model. Section III summarizes related work. Section IV presents the ILP formulation. Results obtained via simulation are discussed in Section V. Finally, in Section VI, conclusions are drawn.

2 Energy consumption model

The power consumption of a router can be divided into two components: traffic dependent and traffic independent components. The traffic independent portion typically represents around 90% of a router's energy consumption. Three major components contribute to a router's power consumption: the router chassis, the router processor and its linecards [8] [9] [10]. The router chassis accounts for an overwhelming portion of the router power consumption. It is, thus, crucial to minimize the amount of chassis to be turned "on" in the network. The power consumption of the linecard is considerably lower than that of the chassis, but this consumption adds up to the total power consumption of the network. A router can have more than one processor allocated to virtual routers in order to satisfy their processing demands. If a single processor is active, the chassis also needs to be active. The chassis should be turned off only when no processors are active. The incorporation of these three components into the energy model differentiates it from other models in the literature which assume a constant value to the energy consumption of a router.

A commonly adopted model [11] [12] for the power consumption of the physical link is employed in this paper. In this model, the energy cost of a physical link depends on the length of the link, that gives the amount of amplifiers required along the link and on the number of used wavelengths. A span distance $\mathcal{P}^s$ determines that every $\mathcal{P}^s$ kilometers (km) a new amplifier is required to properly propagate the signal. Equations 1 and 2 give the energy cost of a physical link.

$$\mathcal{P}^{L}_{u,v} = \mathcal{P}^{\#A}_{u,v} \times \mathcal{P}^{CA} \tag{1}$$

$$\mathcal{P}^{\#A}_{u,v} = \lceil \frac{J_{u,v}}{\mathcal{P}^s} - 1 \rceil + 2 \tag{2}$$

where:

- $\mathcal{P}^{L}_{u,v}$ gives the power consumed by the physical link (u, v);
- $\mathcal{P}^{\#A}_{u,v}$ gives the amount of amplifiers at link (u, v);
- $\mathcal{P}^{CA}$ gives the energy cost of each amplifier;
- $J_{u,v}$ gives the length of link (u, v);

In this paper, it is assumed that the links have a single fiber, and that two amplifiers are added at the endpoints of the link, since signal amplification is needed.

3 Related Work

The seminal work in [13] opened avenues for several others in the literature. Virtualization as a technique for the reduction of power consumption was introduced in [14]. A summary of power consumption elements in IP over WDM is presented in [10]. A Mixed Integer Linear Programming (MILP) model for the design of energy-efficient WDM network was introduced in [11]. It considers an array of physical elements, and traffic aggregation. The power consumption value of linecards is computed as the consumption of a chassis distributed by the number of linecards. The work in [15] considers a wide area network, and evaluates the possibility of turning off elements under QoS constraints. It considers the value of the physical links to be much lower than the power of the nodes. The present paper capitalizes on the advances of energy modeling to provide a realistic description of the mapping problem.

4 Proposed Model

The formulation in this paper models requests for virtual network establishment on network substrates that arrive dynamically. Each request specifies the topology of the virtual network, the resource demanded by the virtual network elements, and the QoS requirements which include a bound on the time to instantiate the VNs and location constrains to instantiate the nodes of the VN.

The model proposed takes the request for the establishment of the virtual network and tries to select which elements of the network substrate should be allocated to instantiate the virtual network. The selection criteria aim at minimizing the energy consumption and yet satisfing the requirements of the request.

The proposal is based on two 0-1 Integer Linear Programming (ILP) sub-models. The model considers realistic parameters, such as the existence of router images located in repositories. The formulation in this paper differs from that in [16] by the introduction of a two step formulation which reduces the computational complexity by reducing the memory consumption. The following notation is used in the formulation of the problem:

- N is the set of physical routers;
- F is the set of physical links, the physical link (n_1, n_2) connects the physical routers n_1 and $n_2 \in N$;
- M is the set of virtual routers;
- V is the set of virtual links, the virtual link (m_1, m_2) connects the virtual routers m_1 and $m_2 \in M$;
- I is the set of images stored in the repository. Each image corresponds to a file with an operating system and a specific set of software ready to be instantiated in a physical router;
- A is the number of available cores in the physical routers; $A(n)$ gives the number of cores of router n;
- P is the set of the number of cores requested by the virtual routers; $P(m)$ gives the number of cores required by the virtual router m;
- C is the set of values of available bandwidth in the physical links; $C(f)$, $f \in F$, gives the available bandwidth in the link f;
- Q is the set of bandwidth values requested by the virtual links; $Q(v)$, $v \in V$, gives the bandwidth required by the virtual link v;

- D is the set of values of delays in the physical links; $D(f)$, $f \in F$, gives the delay in the link f;
- K is the set of values of maximum delay allowed on a virtual link; $K(v)$, $v \in V$, represents the maximum delay allowed in the virtual link v;
- $L_{n,m}$ defines the restrictions related to the location of the physical routers. The value of the variable is 1 if the virtual router m can be mapped onto the physical router n. Otherwise, it is 0. This variable is useful for imposing policy restrictions related to the location of the physical routers. If a user does not want a virtual router m to be mapped onto a physical router, the variables of $L_{n,m}$ must be 0;
- $R_{n,i}$ provides details about the location where images are stored. If the image i is located in a repository with a direct link to the physical router n, the value of the variable is 1. Otherwise, it is 0;
- $E_{m,i}$ is related to software restrictions. If the image i contains all the software requirements (operating system, protocol stacks and kernel modules) required by the virtual router m, the value of the variable is 1. Otherwise, it is 0;
- B is the set of values of the available memory in the physical routers; $B(n)$ represents the memory available in the router n;
- G is the set of image sizes; $G(i)$ represents the size of the image i;
- S is the time threshold for instantiating the virtual network;
- $T_{n,i}$ represents the time the physical router n takes to boot the image i;

The values of $\mathcal{P}^{chassis}$, $\mathcal{P}^{L}$, $\mathcal{P}^{card}$ and $\mathcal{P}^{core}$ are used in the constraints related to detonate the power consumption of the network of chassis, physical link, linecards and cores, respectively.

The inclusion of D, K, $L_{n,m}$, $E_{m,i}$, B, G, S, $T_{n,i}$, I and $R_{n,i}$ in the formulation makes this work unique and realistic due to the consideration of diverse aspects of real networks. The maximum delay allowed in the network links (D, K) affects the QoS furnished to applications sensitive to the delay, specially those involving video and audio. The specific image required by a virtual router should be defined and the content of each repository must be known ($R_{n,i}$) to determine from which repository the image should be downloaded ($I, E_{m,i}$). Locality restrictions and the size of the images should be known since routers have limited storage capacity (B, G) and the size of the image impacts the download time. Moreover, users can have policy issues that prevent the utilization of some physical routers ($L_{n,m}$) or can restrict the solution to employ energy efficient sites. Moreover, the maximum time acceptable to the instantiation of the virtual network is related to the urgency of virtual networks and service prioritization (S, D, K, $T_{n,i}$).

In the formulations, the two following variables define the state of occupancy of the network substrate:

- K_n denotes the number of cores allocated in the physical router n
- $O_{u,v}$ denotes the number of virtual links that use the physical link u, v

The values of K_n and $O_{u,v}$ are used in the computation of α_n and $\beta_{u,v}$, which simplify the objective function:

$$\alpha_n = \lceil \frac{K_n}{K_n + 1} \rceil \tag{3}$$

$$\beta_{u,v} = \lceil \frac{O_{u,v}}{O_{u,v} + 1} \rceil \tag{4}$$

The values of α_n and $\beta_{u,v}$ determine, respectively, whether or not a router and a physical link are already in use.

The solution of the problem is given by the binary variables:

- $X_{n,m,i}$: its value is 1 if the virtual router m is mapped onto the physical router n using the image i; otherwise, it is 0;
- $Y_{u,v,w}$: its value is 1 if the physical path used by the virtual link w includes the physical link (u, v); otherwise, it is 0;
- $Z_{u,v,m}$: its value is 1 if the physical path (u, v) is used to transfer the image requested by the virtual router m; otherwise, it is 0.
- U_n: its value is 1 if the physical router (n) is to be powered on; otherwise, it is 0.
- $W_{u,v}$: its value is 1 if the physical path (u, v) is to be powered on; otherwise, it is 0.

The mapping of the virtual networks is based on the sequential execution of two ILPs. The first (ILP-Green-Mapping) maps the virtual networks onto the substrate. The second (ILP-Green-Image) determines the path in the substrate used to transfer the images.

The ILP-Green-Mapping is formulated as follows:

Minimize

$$\mathcal{P}^{chassis} \sum_{n \in N} (\alpha_n + (1 - \alpha_n) U_n) +$$
$$\mathcal{P}^{core} \sum_{n \in N} \sum_{m \in M} \sum_{i \in I} (X_{n,m,i} \times P(m)) +$$
$$(2\mathcal{P}^{card}_{u,v} + \mathcal{P}^{L}_{u,v}) \sum_{(u,v) \in F} (\beta_{u,v} + (1 - \beta_{u,v}) W_{u,v})$$

subject to

$$\sum_{n \in N} \sum_{i \in I} X_{n,m,i} = 1 \tag{C1}$$
$$\forall m \in M$$

$$\sum_{m \in M} \sum_{i \in I} X_{n,m,i} \leq 1 \qquad (C2)$$
$$\forall n \in N$$

$$\sum_{m \in M} \sum_{i \in I} P(m) \times X_{n,m,i} \leq A(n) \qquad (C3)$$
$$\forall n \in N$$

$$X_{n,m,i} = 0 \qquad (C4)$$
$$\forall n \in N, \forall m \in M, \forall i \in I | L_{n,m} = 0 \text{ or } E_{m,i} = 0$$

$$\sum_{w' \in V} Y_{u,v,w'} \times Q(w') \leq C(w) \qquad (C5)$$
$$\forall w = (u,v) \in F$$

$$\sum_{u \in N} \sum_{v \in N} Y_{u,v,w} \times D(u,v) \leq K(w) \qquad (C6)$$
$$\forall w \in V, (u,v) \in F$$

$$\sum_{m \in M} \sum_{i \in I} X_{n,m,i} \times G(i) \leq B(n) \qquad (C7)$$
$$\forall n \in N$$

$$Y_{u,v,w} = 0 \qquad (C8)$$
$$\forall u, \forall v, \forall w \in V | (u,v) \notin F$$

$$\sum_{f \in N} Y_{n,f,w} - \sum_{f \in N} Y_{f,n,w} = \qquad (C9)$$
$$\sum_{i \in I} X_{n,a,i} - \sum_{i \in I} X_{n,b,i}$$
$$\forall w = (a,b) \in V, \forall n \in N$$

$$X_{n,m,i} \leq U_n \qquad (C10)$$
$$\forall n \in N, \forall m \in M, \forall i \in I$$

$$U_n \leq \sum_{m \in M} \sum_{i \in I} X_{n,m,i} \qquad (C11)$$
$$\forall n \in N$$

$$Y_{u,v,w} \leq W_{u,v} \qquad (C12)$$

$\forall v \in V, \forall (u,v) \in F$

$$W_{u,v} \leq \sum_{v \in V} Y_{u,v,w} \qquad (C13)$$
$\forall (u,v) \in F$

$$X_{n,m,i} \in \{0,1\} \qquad (C14)$$
$\forall n \in N, \forall m \in M, \forall i \in I$

$$Y_{u,v,w} \in \{0,1\} \qquad (C15)$$
$\forall u, \forall v, \forall w \in V$

$$U_n \in \{0,1\} \qquad (C16)$$
$\forall n \in N$

$$W_{u,v} \in \{0,1\} \qquad (C17)$$
$\forall u, \forall v \in V$

The objective function minimizes the power consumed by the request.

Constraint ($C1$) establishes that a virtual router is assigned to a single physical router and that a single image is used to instantiate it. Constraint ($C2$) limits the amount of virtual routers that can be allocated to a physical router per request. Only one virtual router can be allocated to a physical router per request. Constraint ($C9$) ensures that the set of physical links that composes a virtual link is a valid path. It compares the in-degree and the out-degree of each physical router n.

Constraints ($C3$) and ($C7$) express the limitations of the physical routers. They ensure that each physical router will not allocate more than its maximum capacity of cores and memory, respectively.

Constraint ($C4$) guarantees that the virtual routers will be instantiated only using images that meet its software requirements as well as geographic location.

Constraints ($C5$) and ($C6$) express the limitations of the physical links. Constraint ($C5$) ensures that the bandwidth available in each physical link is greater than the bandwidth requirements of all virtual links using it. Constraint ($C6$) establishes that the total delay in the physical path allocated to a virtual link should not exceed the delay threshold allowed for that virtual link.

Constraint ($C8$) guarantees that if (u,v) does not correspond to a physical link, it will never be used in the mapping.

Constraints ($C10$) and ($C11$) express the energy constraints of the physical routers. Constraint ($C10$) ensures that no core can be assigned to a given router without turning on the device first. Constraint ($C11$) ensures that if the router is powered on, then at least one core needs to be assigned to that router.

Constraints ($C12$) and ($C13$) express the energy constraints of the physical links. Constraint ($C12$) ensures that a virtual link can be used on the physical link (u,v) only if the physical link is powered on. Constraint $(C13)$ ensures that if the link is powered on, then at least one virtual link needs to be assigned to that physical link.

Constraints $(C14)$, $(C15)$, $(C16)$ and $(C17)$ define the domains of the binary variables.

After the solution of the ILP-Green-Mapping is found, the values of $X_{n,m,i}$ e $Y_{u,v,w}$ can be used as input to the second formulation, the ILP-Green-Image.

The ILP-Green-Image is formulated as follows:

$$\text{Minimize} \sum_{m \in M} \sum_{u \in N} \sum_{v \in N|(u,v) \in F} Z_{u,v,m} \times D(u,v)$$
$$+ \frac{Z_{u,v,m} \times G(i|X_{n,m,i}=1)}{C(u,v)} \text{ subject to}$$

$$\textstyle\sum_{m \in M} Z_{u,v,m} = 0 \qquad (C18)$$
$$\forall u, \forall v|(u,v) \notin F$$

$$\sum_{j \in N} Z_{u,j,m} - \sum_{j \in N} Z_{j,u,m} = \qquad (C19)$$

$$X_{n,m,i} \times R_{u,i} - X_{n,m,i} \times (1 - \lceil \frac{|u-n|}{\alpha} \rceil)$$
$$\forall m \in M, \forall i \in I, \forall n, u \in N, \alpha = |N|$$

$$Z_{u,v,m} \in \{0,1\} \qquad (C20)$$
$$\forall u, \forall v, \forall m \in M$$

The objective function minimizes the time required to instantiate the virtual network. The time needed to instantiate each virtual router is the sum of the time required to transfer the image and to boot the operating system assuming that two or more images can be transferred simultaneously in the same physical link.

Constraint $(C18)$ guarantees that (u,v) will not be used if it does not belong to the considered substrate. Constraint $(C19)$ establishes that the set of physical links allocated to transfer an image consists of a valid path in the substrate network. Constraint $(C20)$ defines the domains of the variables.

5 Performance Evaluation

To evaluate the performance of the proposed formulation, another optimization model was developed containing similar constraints, but a different objective function: the minimization of the allocated bandwidth. In the remainder of this paper, the proposed formulation is denoted as GREEN, while the formulation which minimizes the allocated bandwidth is denoted as BAND. The formulations were evaluated in dynamic scenarios, in which the availability of resources in the substrate network varies as a function of time.

The average power consumption per request and the amount of bandwidth allocated per request were evaluated as a function of the substrate sizes (number of physical routers) and as a function of the inter arrival time of requests. To assess the effectiveness of the proposed formulation, a simulator was implemented in C++. This simulator receives a description of the substrate network as input and generates requests. Confidence intervals with 95% confidence level were derived using the independent replication method. The ILP formulations were implemented using the CPLEX optimization library version 12.0. The simulations were executed on a computer running the operating system Debian GNU/Linux Squeeze. The computer was equipped with two Intel Xeon 2.27GHz processors, with 6 cores each one, and 6GB of RAM.

Table 1 shows the value of the parameters used. Energy parameters in the simulations were obtained from several sources [8] and they are shown in Table 2.

Table 1: Values of the parameters used in the simulation

Parameter	**Value**
Number of physical nodes	{30 150}
Bandwidth of each physical link	∼10240Mbps
Number of images in the network	3
Simulation time	5000s
Average arrival time per request	{25 50 75 100 125 150 175 200 225 250 275 300}s
Average duration per request	1250s
Number of virtual nodes per request	4
Bandwidth of each virtual link	∼1024Mbps
Maximum time required to instantiate the network	100s
RAM memory	768MB
Image size	128MB
Cores per physical router	6
Cores per virtual router	6
Physical link delay	Defined by BRITE
Virtual link delay	15 × value defined by BRITE
Time required to process the image	10s

Both the topology of the substrate networks and that of the virtual networks were generated using the topology generator `BRITE` [17], with the BA-2 [18] method, a method that generates network topologies similar to the Internet. For the substrate network, the link delays were the values returned by `BRITE`. Since the delay of the links on the virtual networks should be greater than the delays in the links of the substrate network, these delays were defined by multiplying the value returned by `BRITE` by 15.

Table 2: Energy Parameters

Parameter	**Value**
Chassis	10920W
Processor	166W
Line Card	450W
Amplifier	15W

Figure 1 shows the average energy consumption per request as a function of the number of nodes in the substrate for an average interval time of requests of 25 seconds. The average energy consumption increases for both formulations since a higher number of nodes in the substrate implies that mapping tends to use a higher number of nodes. The energy

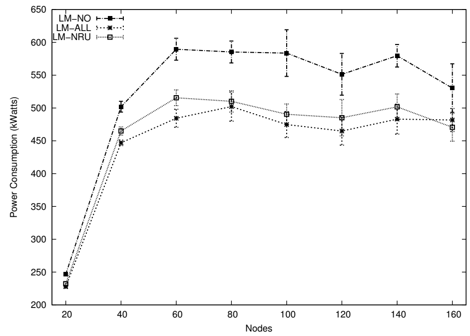

Figure 1: Average Power Consumption per request as a function of the number of nodes of the substrate

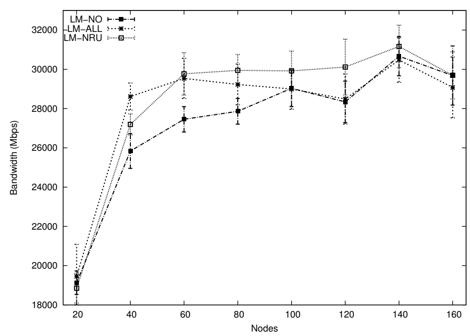

Figure 2: Average Allocated Bandwidth per request as a function of the number of nodes of the substrate

consumption of the chassis is quite high compared to other elements, so the impact on the consumption per request increases since there is a higher number of nodes active. For substrates with more than 120 nodes, the GREEN model tends to allocate cores in routers already active (powered on) and the energy consumption per request stabilizes. However, for the BAND model which does not tend to utilize active routers, the consumption per request tends to increase due to a higher number of routers active. For substrates with 300 nodes GREEN energy reduction was of the order of 50%. Figure 2 shows the average allocated bandwidth per request as a function of the number of nodes of the substrate. As expected, the bandwidth consumption per request is higher for the GREEN model since it tends to use routers already powered regardless of the location of these routers which can imply in long paths between nodes. The bandwidth consumption under the GREEN model is more than that consumed by BAND, but it is important to state that the GREEN model does not violate the QoS requirements of the requests, since the constraints defined in the formulation guarantee the support of these requirements.

Figures 3 and 4 show the average power consumption per request as a function of the interval arrival time of requests for substrates with 30 and 150 nodes respectively. As the inter arrival time decreases, i.e. the arrival rate increases, the power consumption tends to increase since a higher number of routers become active. However, the increase is much

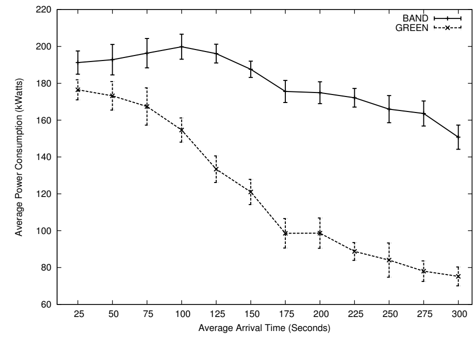

Figure 3: Average Power Consumption (Second set of experiments of a duration of the inter arrival time of request for a substrate with 30 nodes

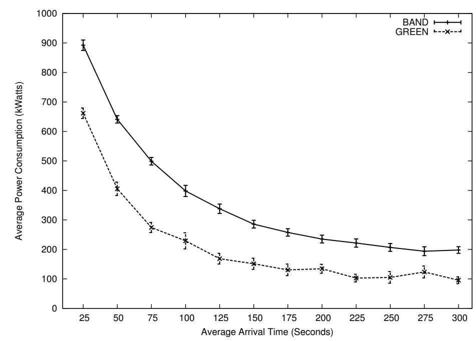

Figure 4: Average Power Consumption per request of a duration of the inter arrival time of request for a substrate with 150 nodes

sharper to the BAND model than to GREEN one. The difference is quite significant and the consumption of BAND can be almost twice for low loads and substrates of 30 nodes and up to 1.5 more for substrates of 150 nodes. However, GREEN consumption of bandwidth (figured not shown due to space limitations) is quite longer. It consumes 3, 5 and 4 times more bandwidth for substrates with 30 and 150 nodes. Moreover, as mentioned before, the GREEN model supports the QoS requirements of the requests.

In summary, results confirm what was expected from the GREEN model. It proposes allocation that saves energy more than a model that does not consider the energy consumption of the network elements. In the attempt to minimize power consumption, more bandwidth is required to allocate the virtual networks on elements that are already powered on since longer paths can be required to connect them. Moreover, the QoS requirements were always supported.

6 Conclusion

A new model to map virtual networks on network substrates with the objective of minimizing energy consumption was presented in this paper. The model is based on an ILP formulations and it considers several realistic parameters neglected by previous works in the literature.

This proposal was compared to another one that minimizes the bandwidth consumption. Results show that acquired power savings per request can be of the order of 50% for some scenarios. Moreover, the QoS requirements of the virtual networks demands were satisfied.

The green model answers the call for an ever growing demand for decreasing the amount of power consumption of communication networks. It can be used for the virtualized network of the future which definitely needs to refrain the consumption of energy in the face of the growth of network demand.

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