Energy efficient architectures for the current and future Internet

(Extended abstract of the MSc dissertation)

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Abstract

The energy consumption is a major concern nowadays not only because of environmental issues but also economical ones. The current Internet infrastructure wastes a lot of energy because the network elements are always working at their full capacity even with a low traffic demand. This energy waste of the Internet can be reduced by allowing some network elements to enter in energy saving modes. However, it may lead to the decrease of the network performance. This work consists on applying an energy saving model to the current Internet architecture and to the PSIRP architecture, taking into account the tradeoff between energy saving and network performance. This is mainly achieved by classifying the network elements according to their importance in the packet delivery process. Also, this solution was implemented and evaluated using the NS3 simulator. The evaluation results show that with a low traffic demand the energy consumption can be reduced by 45% in average. On the other hand, with a high traffic demand the energy consumption is reduced by 23% in average.

Keywords: *Internet, Clean Slate Design, Energy consumption, Energy saving, Traffic engineering, Turning off network elements.*

1 Introduction

The Internet adoption has significantly grown in the past two decades. In fact, the Internet has become essential in our daily live. Despite its importance, the Internet also has its share in the overall energy consumption of modern society, which according to [1] is about 5% of the total energy consumption of developed countries.

The energy consumption is a major concern nowadays not only for environmental, but also economical reasons. Due to this fact, several research works are being proposed in the green networking area, which focus on bringing energy awareness to the underlying network infrastructure that effectively lacks energy saving measures.

In the current network design it is considered both Quality of Service (QoS) and availability constraints. This mainly happens because it is assumed a permanent high load in the network, which is not always the case especially during night hours. This makes it possible to induce network elements into a energy saving mode during the periods of low network load [2].

Applying energy saving strategies in wired networks often leads to a performance reduction and even in some cases to a loss of connectivity. The challenge behind a smart energy management is being able to reduce the network energy consumption without too much impact in its performance. This document addresses the work done in this area and proposes a solution that tries to achieve a good tradeoff between energy savings and network performance.

1.1 Motivation

The energy consumption is a major concern nowadays mainly because of the global warming effect, which is leading to major climate changes. A recent report from the European Union (EU) estimates a necessary reduction of about 15% - 30% in the emission of Greenhouse Gas (GHG) until 2020, in order to keep the increasing of the temperature below 2% [3].

Even though the energy spent by the Internet may be negligible in comparison with the rest of the society colossal energy consumption, it is important that significant work is done to reduce the energy consumption of the Internet, thus contributing for the reduction of the GHGs emission.

When building a more energy efficient architecture it must be taken into account the impact produced in the performance of the network. This is important, because many of the current Internet services require high bandwidth, e.g high definition content. Therefore it is important to research and develop efficient energy saving models that can reduce the energy consumption of the current Internet, without producing a major impact in the performance of the network.

The unbounded energy consumption is mostly caused by two main factors. Primarily, the energy consumption does not vary linearly according to the utilization of network nodes and links, which ideally should be zero in case of no utilization. On the other hand, the network nodes are always powered on to maintain the network connectivity at all times. By enabling the network elements to enter in an energy saving mode, it will be possible to greatly reduce the energy consumption when they are idle or underused. This will not only allow a reduction in the emissions of GHG but will also allow a reduction in energy associated costs.

1.2 Objectives

This work aims to develop research on the technologies for the future Internet architecture, being also addressed energy saving models that will allow a reduction in the energy consumed by the Internet. Therefore the following goals were defined for this work:

- Evaluate the current Internet model in terms of energy consumption and throughput.
- Evaluate a completely new architecture and its applicability in the future Internet architecture.
- Perform an evaluation of the energy consumption of both systems.
- Reduce the overall energy consumption of the network without too much impact in its performance.

1.3 Document Organization

The remaining contents of this document are organized as follows: section 2 presents the state of the art on proposals for the future Internet architecture and energy saving techniques; section 3 describes the proposed solution which aims to reduce the energy consumption; section 4 describes the evaluation results of the proposed solution; section 5 describes the future work to be done; Finally, section 6 gives a brief conclusion and summary of the results of the proposed solution.

2 Related Work

The main goals of this section are to provide an overview of the issues of the current Internet architecture and to identify the contribution of the different proposals for the future Internet architecture. Finally it will also be discussed energy saving techniques which improve the energy efficiency of the Internet.

2.1 Future Internet Proposals

Despite the tremendous success of the Internet, its current architecture may not be the ideal solution for issues, like: security, mobility, manageability, dependability and scalability [4]. These problems do not have a trivial solution, because it is difficult to address them without increasing the complexity of the architecture. These issues can prevent the achievement of a better performance for some communication technologies, such as fibre optics and radio transmissions [5].

As a consequence of the aforementioned problems, new solutions and even different paradigms are being researched to mitigate them. Hereafter, relevant work for this thesis will be presented.

There is a growing need for information-centric networking, due to the increasing usage of overlay networks for information dissemination. In this situation, users will exchange pieces of information among themselves to reduce the load from central servers. Taking this into consideration, the Wired and Wireless World Wide Architecture and Design (4WARD) approach is to make use of virtual networks over multiple physical infrastructures, trying to achieve some sort of separation between the physical and the logical topology of the network and allowing an efficient management of the available network resources [4].

The Autonomic Network Architecture (ANA) makes an important contribution to the future Internet due to the support of network self management and self optimization. Besides this, it provides good flexibility in terms of the utilization of different networking schemes and protocols, also allowing the easy deployment of new ones. Last but not least it provides good support for mobility, allowing a better connectivity and performance when moving between different networks, e.g. wireless networks [6].

Nowadays the IP addresses are used for identifying both networks and communication points, which provides some security but at the cost of mobility. In this sense the Forwarding directive, Association, and Rendezvous Architecture (FARA) proposes a solution for solving this problem without the creation of a new identifier name space. This way it is possible to separate entities from their respective location, which offers better support for entity mobility [7].

The New Internet Routing Architecture (NIRA) was designed to allow users the possibility to choose their own domain-level routes. A domain-level route is characterized as the domains that the packet needs to pass until it reaches its destination, differing from router-level route which is described as the routers that forward the packet to the destination. Also, it avoids the use of a global link-state protocol by configuring link-state messages to be propagated within a provider hierarchy [8].

The Publish-Subscribe Internetworking Routing Paradigm (PSIRP) approach uses the publish-subscribe paradigm, whose architecture is based in the information and not in the network nodes. This way the receivers have full control of the information that they want to consume.

Most publish-subscribe architectures are composed of three major components, which are: publishers, subscribers and routing nodes (brokers). The publishers are responsible for feeding the network with information to be consumed, i.e. publications. The subscribers are the consumers of information by expressing their interest on some published items using subscription messages. The brokers are responsible for forwarding the data between the publishers and the subscribers by matching the interests of the subscribers with the information published. So the brokers or Rendezvous Points (RPs) have the responsibility to route, forward and allowing the delivery of data from publishers to subscribers. Using this kind of architecture the publishers and subscribers do not need to be aware of the existence of each other [9].

The Explicit Control Protocol (XCP) is a window-based protocol, like Transmission Control Protocol (TCP) and Stream Control Transmission Protocol (SCTP), which implements congestion control at the end-points of a connection, offering high end-to-end throughput. The TCP protocol is commonly used in the current Internet for congestion control, but it is not capable of offering high throughput since it is inversely proportional to the packet drop rate. For this reason, it is needed a new congestion control protocol that can provide better performance than TCP in conventional environments and that can still be efficient, fair, and stable when the delay of the communication increases[10].

2.2 Sustainable Internet Technology

The constant growth of the Internet for several years resulted in a significant increase of the amount of energy required to operate all the network devices, which may be working all day long. This huge energy consumption has become problematic, since the world environmental conditions are becoming more and more unpredictable due to the emission of GHGs to the atmosphere. This leads to the need of finding good energy saving solutions, not only to reduce environmental damages but also to reduce the associated energy costs [11, 12].

The energy efficiency is a problem that will affect both wired networks and service infrastructures. This is highly dependent on the arrival of new services, because of the traffic increase that may be originated by them [13]. Next it will be discussed some of the work that is being done in the energy efficiency field for the future Internet architecture.

2.2.1 Power Management and Network Design

In legacy networks, energy consumption was not a major concern, not being important enough to be addressed in their design. The major concerns of those systems were mainly: reliability, cost-effectiveness, robustness, service quality and service availability. With the increase of data traffic and new applications, the Internet is consuming more and more energy. To prevent the increasing of the energy consumption it is important to explore new solutions that will allow a better energy management. Hereafter it will be discussed some energy saving solutions [12]:

- *Energy Saving Mode:* The idea of this solution is to put equipments to sleep, since there is no need to waste energy when the equipment is not actually being used. This can be done at different levels, which are: at individual level, where switches, routers or other devices are put to sleep; at network level, combining sleep with routing changes and the use of bandwidth aggregation, so that when in low activity only the idle equipments are put to sleep; finally, at Internet level this can be done by changing the network topology, allowing the adaptation of routes to different network loads.

- *Adaptive Link Rate (ALR):* In this approach, the link rate will be dynamically changed according to its utilization. This is done by exploiting the variable periods of idleness between consecutive burst of packets. This technique is being adopted by IEEE Energy Efficient Ethernet (EEE)[1] [14].

- *System Redesign:* The idea behind this concept is to design new network architectures and protocols, taking into account the energy consumption constraint. Embedding energy saving mechanisms directly in new architectures has a tremendous impact in the reduction of energy consumption. One idea may pass by limiting the packet processing that needs more energy to only a group of routers and the creation of new data link and routing protocols that are able to work in on-off networks [12].

[1] IEEE 802.3 Energy Efficient Ethernet Study Group. `http://grouper.ieee.org/groups/802/3/eee_study/index.html` (Last access: 13-03-2012)

2.2.2 Energy Saving Models

In order to achieve an important reduction in the energy consumption of networks, it must be explored the possibility of making routing and traffic engineering decisions based on the utilization and criticality of the network elements. This way, it is possible to achieve a reduction of the overall energy consumption of the network by dynamically turning off network nodes and links when their resources are not required. Hereafter, it will be discussed some solutions based on the aforementioned concepts.

- *Dynamic Link Metric:* The basic idea of the algorithm presented in [15] is to aggregate traffic to the most used links. The links with no traffic load will be turned off, allowing some energy savings. Also, it will be defined a threshold to avoid traffic congestion in a link by restraining the allowed amount of traffic. A link will be considered to be congested when its traffic load exceeds the threshold, making it necessary to switch back on some other link to carry the remaining traffic. This will be achieved by dynamically changing the weight of the link, transferring the traffic load to most commonly used links.

- *Switching-Off Network Elements:* In [16] it is explored the possibility of switching off not only network links but also network nodes. The goal of the proposed algorithm is to find the minimum set of routers and links that must be powered on so that the total energy consumption of the network can be reduced. This work followed an heuristic approach to solve the energy consumption problem.

- *Green-Game:* The Green-Game [2] proposes a model that tries to solve a resource consolidation problem by taking into account both the traffic load and the network topology. Using this information it will be possible to rank the contribution of each node in the packet delivery process. This can achieve a good tradeoff between performance and energy savings, since the ranking combines traffic-aware and topology-aware constraints. Taking this into consideration the Green-Game will try to find the set of nodes that can safely be turned off on low load networks.

2.2.3 Ranking Network Elements

In order to efficiently choose which network elements will be turned off, it is important to rank each one according to its criticality in the network. This can be done by looking to the network topology or to the traffic volume passing through the network element. The most widely used topology based rankings are: Degree centrality, connectivity of each node; Betweenness centrality, number of shortest-paths that passes through each node; Closeness centrality, average distance between a couple of nodes; Eigenvector centrality, importance of the neighbours of each node. Lastly, the traffic volume based rankings consist only on ordering nodes according to the network elements utilization [2].

3 Architecture

The proposed solution embeds energy awareness to the IP network architecture and to the PSIRP network architecture. This is done by controlling the working state of network elements and by exploring their idleness periods. This way, it will be possible to turn off the unused network elements. It will also be used traffic aggregation to give an opportunity for underused network elements to be turned off. Hereafter, it will be explained in more detail the implemented modules for the proposed architecture.

3.1 Energy Consumption Model

In this section it will be described the energy consumption model used for calculating the overall network energy consumption of the implemented architectures. This will allow to evaluate the energy savings that may be achieved when enabling the energy saving module.

To accurately evaluate the energy savings, it is desirable that the energy consumption model can represent a good estimation of the energy consumed by real network devices. The implemented energy consumption model was based on the work in [17]. According to this model, the energy consumption of each network element can be summarized by Table 1. The C parameter represents the switching capacity of a network node which is the double of the sum of the capacity of all its links (see Equation 1).

$$C(n) = 2 \sum_{(i,j)\in\mathcal{L}} c_{ij} \tag{1}$$

Network Element	$\mathbf{E_0}$ [Watt]	M [Watt]
Nodes	$0.85C^{2/3}$	$C^{2/3}$
(0-100) Mbps links	0.48	0.48
(100-600) Mbps links	0.90	1.00
(600-1000) Mbps links	1.70	2.00

Table 1: Energy consumption of the network elements.

The total network energy consumption can be defined as the amount of energy spent by all nodes and links that belong to the network topology and that are powered on. When a network element is powered on it consumes a constant amount of energy, E_0, even when its utilization is zero. If its utilization is greater than zero, the energy consumption of the network element will be increased by a fraction (link/node utilization) of the difference between M and E_0, also denoted as E_f. According to this model, the total network energy consumption can be represented by Equation 2.

$$E_T = \frac{1}{2} \sum_{(i,j)\in\mathcal{L}} \left(\left(lu_{ij} + lu_{ji} \right) E_{fij} + x_{ij} E_{0ij} \right) + \sum_{n\in\mathcal{N}} \left(nu_n E_{fn} + x_n E_{0n} \right) \tag{2}$$

3.2 Energy Saving Algorithm

The proposed algorithm aims to reduce the overall network energy consumption by exploring the possibility of turning off the network elements, nodes or links, which are not being used. This has to be done taking into account the resulting impact in the performance of the network. To achieve the best tradeoff between energy consumption and performance, the following questions were taken into consideration during the design of the energy saving algorithm.

- *How to aggregate traffic to most frequently used links?*
- *Which are the network elements that can be turned off? In which sequence?*
- *When to turn back on links, in order to reduce the impact in the network performance?*

For the purpose of saving energy, the algorithm will turn off the network elements that are not being used. The network elements to be turned off must be carefully selected in order to reduce the inevitable impact in the network performance. Hereafter it will be explained how the algorithm will try to achieve the best tradeoff between energy savings and network performance.

The algorithm is divided in two main functions, which are: the traffic aggregation and the selection of the network elements to be turned off. Firstly, the use of traffic aggregation will allow the possibility of turning off the underused links by transferring their traffic to other links which have higher utilization. Using this mechanism it will be possible to induce the underused links to an idle mode, allowing for a greater number of network elements to be turned off. Lastly, the selection algorithm will choose the network elements to be turned off and in which order. This will greatly affect energy savings and network performance. The detailed steps of the algorithm are enumerated below:

1. **Check the utilization of every link:** For each node in the network, it will be analysed the utilization of all its links. When the utilization of a link, lu, exceeds the threshold, its weight will be increased to reduce its utilization. The links with a utilization below the threshold will become candidates for a weight decrease (see Algorithm 1). Only the link with higher utilization among the candidates will have a decrease in weight, which may allow some traffic to be aggregated into this link (see Equation 4). The modification of the link weight takes into account the remaining traffic, λ, that can be allocated to it (see Equation 3). Lastly, the links that are not being used will be chosen as candidates for the turn off procedure.

$$\lambda(i,j) = |1 - lu_{ij}| \tag{3}$$

$$cost'(i,j) = \begin{cases} \lambda_{ij} * cost_{ij}, & lu_{ij} \le threshold \\ \dfrac{cost_{ij}}{\lambda_{ij}}, & lu_{ij} > threshold \end{cases} \tag{4}$$

Algorithm 1 The traffic engineering algorithm.

```
for i = 1 → N do
  for j = 1 → L do
    u ← LinkUtilization(i, j)
    if u > threshold then
      IncreaseWeight(i, j)
    end if
    j ← j + 1
  end for
  Decrease weight of the most used link of the node below the threshold
  i ← i + 1
end for
```

2. **Ranking the network elements:** In this step it will be assigned a ranking to each network element that has been selected as candidate to be turned off. This ranking will reflect the importance of the network element in the network. This way it will be possible to specify the sequence in which the network elements will be turned off, starting with the least important ones. In the ranking it will be used the local centrality [18] measure to classify the importance of each network element to the network topology. It was chosen this measure because of its low complexity and because it is more accurate than degree centrality. The local centrality of the network node v, $C_L(v)$, is then defined as

$$Q(u) = \sum_{w\in\Gamma(u)} N(w) \tag{5}$$

$$C_L(v) = \sum_{u \in \Gamma(v)} Q(u) \quad (6)$$

where $\Gamma(u)$ is the set of the nearest neighbours of node u and $N(w)$ is the number of the nearest and the next nearest neighbours of node w. The ranking of network elements will take into consideration both the history of utilization and the local centrality of the network element. The ranking of links and nodes are described below:

- Links: The ranking of links will be calculated using Equation 7, where H_{lu} is the history of utilization of a link. This computation will then be used to order the links by ranking. The links with the same ranking will be reordered by their local centrality, C_L.

$$\mathcal{R}_L(i,j) = (C_L(i) + C_L(j)) \times H_{lu}(i,j) \quad (7)$$

- Nodes: The ranking of nodes will be calculated using Equation 8, where H_{nu} is the history of utilization of a node. As for the links, this computation will allow to order the network nodes according to their ranking. The nodes with the same ranking will be reordered by their local centrality, C_L.

$$\mathcal{R}_N(n) = C_L(n) \times H_{nu}(n) \quad (8)$$

3. **Turn off the network elements:** With the output of the previous step, each of the chosen network elements will be possibly turned off (see Algorithm 2). The links will be turned off if the network remains connective, i.e. without causing partitions in the network. On the other hand, turning off nodes is not a trivial operation because it would cause packets to be lost, since the receivers of the packets would be unavailable. Because of this and of the existing technology the nodes will only be put to sleep instead of fully switched off. So, when a node enters in sleep mode it will wake up after a fixed period of time. A node can only enter in sleep mode if the following conditions are met:

   (a) No remaining traffic in any of its links.

   (b) The remaining nodes of the network can still communicate with each other.

   (c) All of its neighbours which are in sleep mode can rejoin the network in its absence.

   If the above conditions are all satisfied then the node will go to sleep and all of its active links will be turned off. After the sleeping period, the node will verify if the network needs its presence, will enter in the pre wake-up state, because of pending packets destined to it or the network performance has dropped too much. If its presence is not required then the node will go to sleep again, otherwise the node will be turned on and will remain waken as long as the algorithm decides to put it to sleep mode again.

Algorithm 2 Turning off network elements.

```
SortByRank(nodes)
for n = 1 → N do
   if CanGoToSleep(n) then
      Sleep(n)
   end if
   n ← n + 1
end for
SortByRank(links)
for l = 1 → L do
   if CanBeTurnedOff(l) then
      TurnOff(l)
   end if
   l ← l + 1
end for
```

Finally, the algorithm may be forced to turn back on some links to avoid network congestion in the case of high traffic demand. These links will be reconnected taking into account their significance in the network, starting with the most important ones.

4 Evaluation

In this section it will be discussed the experimental results of the implemented solution, with the main goal of verifying the tradeoff between energy savings and network performance. This evaluation will be carried on both IP based and PSIRP based architectures.

The system will be evaluated on two different topologies with both light and heavy traffic. The evaluation results will be obtained by network simulation, using the NS3 simulator.

4.1 Network topologies

For the evaluation it was considered two different network topologies to be used in the experimental scenarios, which allows to verify the adaptation of the energy saving algorithm in different networks.

To provide a more realistic scenario it was chosen two topologies from real networks, the Abilene and the COST 239 networks. The chosen network topologies vary in the number of links. The weight of the links were randomly chosen between the values 1 and 10. Also, it will be used links with a capacity of 10 Mbps. The main characteristics of the topologies are summarized in Table 2.

Network	Nodes	Links	Degree	Ref.
Abilene	11	14	2.55	[19]
COST 239	11	26	4.73	[20]

Table 2: The network topologies used in evaluation.

4.2 Experimental Scenarios

In this section it will be presented the evaluation results of the solution in the different network scenarios. The presented scenarios will test the adaptation of the energy saving algorithm to different loads of traffic. To perform this evaluation the following metrics were defined:

- **Throughput:** Gives the packet delivery average rate.
- **Delay:** Gives the average time that a packet needs to go from the source to the destination.
- **Link Utilization:** Gives the average link utilization of the network.
- **Energy:** Gives the overall energy consumption of the network.

The evaluation results were obtained by running the simulation 40 times for each experimental scenario, being calculated the average and the standard deviation. With this results it will be analysed the tradeoff between network performance and energy savings for each of the chosen experimental scenarios.

4.2.1 Light Traffic Scenario

This section describes the evaluation results of the solution with low traffic demand. In this situation, it will be possible to achieve good energy savings because there will be some unused network elements which will be turned-off. Due to the low traffic demand it is not expected a major performance reduction of the network. Lastly, the traffic conditions of this scenario are described in Table 3.

Traffic Size	Inter-Packet Interval
100 KB	880 μs

Table 3: The traffic conditions in a light scenario.

- **Without the energy saving algorithm:** In Table 4 and Table 5 are presented the results obtained by injecting a small amount of traffic in both network topologies and by using the IP/PSIRP architectures. In this situation, the energy saving algorithm is disabled, serving as base for a comparison between the previously defined metrics in a low traffic scenario.

Abilene Network Topology		
Metric	**AVG ($\tilde{x}$)**	**STD (σ)**
Throughput (Mbps)	8.536	0.166
Delay (ms)	2.530	0.192
Link Utilization (%)	17.822	0.011
Energy (W)	12.318	0.198
COST 239 Network Topology		
Metric	**AVG ($\tilde{x}$)**	**STD (σ)**
Throughput (Mbps)	8.852	0.099
Delay (ms)	1.646	0.097
Link Utilization (%)	6.872	0.003
Energy (W)	18.369	0.152

Table 4: The Dijkstra evaluation without the energy saving algorithm in a low traffic scenario.

Abilene Network Topology		
Metric	**AVG ($\tilde{x}$)**	**STD (σ)**
Throughput (Mbps)	8.830	0.165
Delay (ms)	2.340	0.189
Link Utilization (%)	16.601	0.010
Energy (W)	12.267	0.127
COST 239 Network Topology		
Metric	**AVG ($\tilde{x}$)**	**STD (σ)**
Throughput (Mbps)	9.375	0.075
Delay (ms)	1.407	0.068
Link Utilization (%)	5.951	0.002
Energy (W)	18.349	0.130

Table 5: The PSIRP evaluation without the energy saving algorithm in a low traffic scenario.

- **With the energy saving algorithm:** In Table 6 and Table 7 are presented the results obtained by injecting a small amount of traffic in both network topologies and by using the IP/PSIRP architectures. In this situation, the energy saving algorithm is enabled.
- **Comparison:** In Table 8 is given the results of the comparison made between disabling and enabling the energy saving algorithm. The results show that in a

Abilene Network Topology		
Metric	**AVG ($\widetilde{x}$)**	**STD (σ)**
Throughput (Mbps)	7.650	0.244
Delay (ms)	3.137	0.326
Link Utilization (%)	18.909	0.013
Energy (W)	8.735	0.331
COST 239 Network Topology		
Metric	**AVG ($\widetilde{x}$)**	**STD (σ)**
Throughput (Mbps)	7.793	0.223
Delay (ms)	2.132	0.237
Link Utilization (%)	7.302	0.006
Energy (W)	8.493	0.430

Table 6: The Dijkstra evaluation with the energy saving algorithm in a low traffic scenario.

Abilene Network Topology		
Metric	**AVG ($\widetilde{x}$)**	**STD (σ)**
Throughput (Mbps)	8.009	0.275
Delay (ms)	2.972	0.271
Link Utilization (%)	18.028	0.010
Energy (W)	8.614	0.341
COST 239 Network Topology		
Metric	**AVG ($\widetilde{x}$)**	**STD (σ)**
Throughput (Mbps)	8.594	0.162
Delay (ms)	1.745	0.109
Link Utilization (%)	6.280	0.003
Energy (W)	8.034	0.280

Table 7: The PSIRP evaluation with the energy saving algorithm in a low traffic scenario.

low traffic scenario it can be achieved energy savings above 25% at the cost of approximately 11% of throughput. Also, in the worst cases the energy saving algorithm will increase the average link utilization by ∼9% and the delay by ∼30%.

4.2.2 Heavy Traffic Scenario

This section describes the evaluation results of the solution with high traffic demand. In this situation, the solution will be tested in a more realistic scenario, being expected a low reduction in the energy consumption. Some network links may be turned off, but due to performance constraints they will eventually be turned on again. Lastly, the traffic conditions of this scenario are described in Table 9.

- **Without the energy saving algorithm:** In Table 10 and Table 11 are presented the results obtained by injecting a large amount of traffic in both network topologies and by using the IP/PSIRP architectures. In this situation, the energy saving algorithm is disabled, serving as base for a comparison between the previously defined metrics in a heavy traffic scenario.

Abilene Network Topology		
Metric	**Dijkstra**	**PSIRP**
$\Delta_{\text{Throughput}}$ (%)	-10.386	-9.294
Δ_{Delay} (%)	24.013	27.013
$\Delta_{\text{LinkUtilization}}$ (%)	6.103	8.597
Δ_{Energy} (%)	-29.089	-29.783
COST 239 Network Topology		
Metric	**Dijkstra**	**PSIRP**
$\Delta_{\text{Throughput}}$ (%)	-11.97	-8.33
Δ_{Delay} (%)	29.53	24.06
$\Delta_{\text{LinkUtilization}}$ (%)	6.26	5.54
Δ_{Energy} (%)	-53.77	-56.22

Table 8: The impact of the energy saving algorithm in a low traffic scenario.

Traffic Size	Inter-Packet Interval
1 MB	400 μs

Table 9: The traffic conditions in a heavy scenario.

Abilene Network Topology		
Metric	**AVG ($\widetilde{x}$)**	**STD (σ)**
Throughput (Mbps)	6.184	0.327
Delay (ms)	4.992	0.889
Link Utilization (%)	39.427	0.006
Energy (W)	56.184	0.475
COST 239 Network Topology		
Metric	**AVG ($\widetilde{x}$)**	**STD (σ)**
Throughput (Mbps)	8.616	0.076
Delay (ms)	1.755	0.056
Link Utilization (%)	14.694	0.003
Energy (W)	83.777	0.140

Table 10: The Dijkstra evaluation without the energy saving algorithm in a high traffic scenario.

- **With the energy saving algorithm:** In Table 12 and Table 13 are presented the results obtained by injecting a large amount of traffic in both network topologies and by using the IP/PSIRP architectures. In this situation, the energy saving algorithm is en-

Abilene Network Topology		
Metric	**AVG ($\widetilde{x}$)**	**STD (σ)**
Throughput (Mbps)	6.309	0.415
Delay (ms)	5.219	1.753
Link Utilization (%)	37.080	0.007
Energy (W)	56.369	1.316
COST 239 Network Topology		
Metric	**AVG ($\widetilde{x}$)**	**STD (σ)**
Throughput (Mbps)	8.895	0.056
Delay (ms)	1.554	0.032
Link Utilization (%)	13.271	0.002
Energy (W)	83.610	0.152

Table 11: The PSIRP evaluation without the energy saving algorithm in a high traffic scenario.

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Abilene Network Topology		
Metric	**AVG ($\widetilde{x}$)**	**STD (σ)**
Throughput (Mbps)	5.647	0.201
Delay (ms)	5.588	0.629
Link Utilization (%)	39.250	0.006
Energy (W)	52.379	0.855
COST 239 Network Topology		
Metric	**AVG ($\widetilde{x}$)**	**STD (σ)**
Throughput (Mbps)	7.688	0.092
Delay (ms)	2.154	0.076
Link Utilization (%)	14.973	0.002
Energy (W)	56.955	0.741

Table 12: The Dijkstra evaluation with the energy saving algorithm in a high traffic scenario.

- **Comparison:** In Table 14 is given the results of the comparison made between disabling and enabling the energy saving algorithm. The results show that in a high traffic scenario it can not be achieved energy savings of no more than 36% at the cost of approximately 11% of throughput. Also, in the worst cases the energy saving algorithm will increase the average link utilization by ∼5% and the delay by ∼30%.

5 Future Work

As future work, we would like to perform a further evaluation of the system in a wider set of network topologies and traffic conditions, giving a lot of focus to the robustness in the case of failures.

Abilene Network Topology		
Metric	**AVG ($\widetilde{x}$)**	**STD (σ)**
Throughput (Mbps)	5.685	0.233
Delay (ms)	5.706	0.753
Link Utilization (%)	37.829	0.007
Energy (W)	52.096	0.968
COST 239 Network Topology		
Metric	**AVG ($\widetilde{x}$)**	**STD (σ)**
Throughput (Mbps)	7.949	0.097
Delay (ms)	2.008	0.072
Link Utilization (%)	13.927	0.002
Energy (W)	54.849	0.698

Table 13: The PSIRP evaluation with the energy saving algorithm in a high traffic scenario.

Abilene Network Topology		
Metric	**Dijkstra**	**PSIRP**
$\Delta_{\text{Throughput}}$ (%)	-8.678	-9.892
Δ_{Delay} (%)	11.947	9.336
$\Delta_{\text{LinkUtilization}}$ (%)	-0.448	2.021
Δ_{Energy} (%)	-6.773	-7.580
COST 239 Network Topology		
Metric	**Dijkstra**	**PSIRP**
$\Delta_{\text{Throughput}}$ (%)	-10.77	-10.63
Δ_{Delay} (%)	22.72	29.22
$\Delta_{\text{LinkUtilization}}$ (%)	1.90	4.94
Δ_{Energy} (%)	-32.02	-34.40

Table 14: The impact of the energy saving algorithm in a high traffic scenario.

Also, we would like to study the applicability of the energy saving algorithm in conjunction with a distance-vector routing protocol.

Finally, we would like to implement and evaluate the energy saving algorithm in real networks. In this work, the energy saving algorithm was only evaluated by making use of network simulation.

6 Conclusions

This article addresses the most significant problems of the current Internet architecture, being given special attention to the energy consumption issue. Throughout the article, it is reviewed the efforts that are being made by the research community to reduce the energy consumption of the Internet infrastructure. Also, it is proposed a solution that enables energy awareness in the Internet architecture by turning off unused network elements.

The implemented energy saving solution makes traffic engineering decisions to aggregate traffic to most used links, which will allow the possibility of inducing underused links to an idle mode. The unused network elements, nodes or links, can be turned off if the network remains connective. Also, it is proposed a ranking mechanism that classifies the importance of a network element. This mechanism is of extreme importance to achieve a good trade off between energy savings and network performance, mainly because it will turn off in first place the network elements that are less important to the packet delivery process.

The evaluation of the solution shows that significant energy savings can be achieved in a low traffic scenario without too much impact in the network performance. In a heavy traffic scenario, the proposed solution also manages to reduce the energy consumption but in a smaller percentage.

References

[1] Global e-Sustainability Initiative (GeSI). Smart 2020 report: Global ict solution case studies. Technical report, http://www.smart2020.org/publications/, 2008.

[2] A.P. Bianzino, C. Chaudet, D. Rossi, and et al. The green-game: Striking a balance between qos and energy saving. In *Teletraffic Congress (ITC), 2011 23rd International*, pages 262 –269, September 2011.

[3] A. Bianzino, C. Chaudet, D. Rossi, and et al. A survey of green networking research. *Communications Surveys Tutorials, IEEE*, PP(99):1 –18, 2010.

[4] N. Niebert, S. Baucke, I. EI-Khayat, and et al. The way 4ward to the creation of a future internet. *IEEE*, 2008.

[5] G. Tselentis. *Towards the Future Internet*, pages 91 –101. IOS Press, 2009.

[6] M. Siekkinen, V. Goebel, T. Plagemann, and et al. Beyond the future internet – requirements of autonomic networking architectures to address long term future networking challenges. *Proceedings of the 11th IEEE International Workshop on Future Trends of Distributed Computing Systems*, 2007.

[7] D. Clark, R. Braden, A. Falken, and et al. Fara: Reorganizing the addressing architecture. *ACM Sigcomm Workshops*, August 2003.

[8] X. Yang, D. Clark, and A. Berger. Nira: A new interdomain routing architecture. *IEEE/ACM Transactions on Networking*, 15(4), August 2007.

[9] N. Fotiou, D. Trossen, and G. Polyzos. Illustrating a publish-subscribe internet architecture. *Telecommunication Systems, Springer*, 2010.

[10] Y. Zhang and T. Henderson. An implementation and experimental study of the explicit control protocol (xcp). *IEEE*, 2:1037 –1048, 2005.

[11] M. Baldi and Y. Ofek. Time for a "greener" internet. *IEEE*, 2009.

[12] H. Mellah and B. Sansò. Review of facts, data and proposals for a greener internet. *ICST Broadnets*, 2009.

[13] R. Bolla, R. Bruschi, F. Davoli, and et al. Energy efficiency in the future internet: A survey of existing approaches and trends in energy-aware fixed network infrastructures. *IEEE Communications Surveys*, 2010.

[14] C. Gunaratne, K. Christensen, B. Nordman, and et al. Reducing the energy consumption of ethernet with adaptive link rate (alr). *IEEE Transactions on Computers*, 57(4), April 2008.

[15] S. Gao, J. Zhou, T. Aya, and et al. Reducing network power consumption using dynamic link metric method and power off links.

[16] L. Chiaraviglio, M. Mellia, and F. Neri. Energy-aware networks: Reducing power consumption by switching off network elements.

[17] A. Bianzino, C. Chaudet, F. Larroca, and et al. Energy-aware routing: A reality check. In *GLOBECOM Workshops, 2010 IEEE*, pages 1422 –1427, December 2010.

[18] D. Chen, L. Lü, M. Shang, and et al. Identifying influential nodes in complex networks. *Physica A: Statistical Mechanics and its Applications*, 391(4):1777 –1787, February 2012.

[19] M. Yu, M. Thottan, and L. Li. Latency equalization as a new network service primitive. *Networking, IEEE/ACM Transactions on*, 20(1):125 –138, February 2012.

[20] P. Batchelor, B. Daino, P. Heinzmann, D. R. Hjelme, R. Inkret, H. A. Jager, and et al. Study on the implementation of optical transparent transport networks in the european environment - results of the research project cost 239. *Photonic Network Communications*, 2:15 –32, 2000.