A Survey on Energy Efficiency for the Future Internet

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Abstract—**Internet infrastructure energy consumption is a major topic of research nowadays due to environmental and economical concerns. Therefore, it is increasingly important new solutions that decrease energy consumption, but without impairing network throughput and costs. Hence, it is important to survey and categorize current techniques, not only applicable to IP networks, but that can also be potentially useful for the future Internet architectures, such as Publish-Subscribe architectures. Therefore, to achieve such goals this paper presents a survey on energy efficient architectures and functional mechanisms (such as energy adaptive routing) for the current and future Internet. The main goals are: to provide an overview of the issues of the current Internet architecture; to identify the contribution of the different proposals for the future Internet architecture; and to discuss energy saving techniques which improve Internet energy efficiency.**

Index Terms—**Energy, future internet architectures, energy efficient routing, traffic engineering, survey.**

I. Introduction

Energy issues are a growing concern on the early XXI century [1]. According to [2], energy consumption by telecommunication networks account to about 5% of the total energy consumption of developed countries, being a major concern nowadays not only for environmental, but also due to economical reasons. Indeed, the energy spent by telecommunications network equipment represents already a large bill on network operations' costs.

Hence, significant research work in the green networking area has been propose solutions which focus on bringing energy awareness to the underlying network infrastructure, that currently lacks effective energy saving measures. This paper aims to present a comprehensive survey of the main energy saving techniques presented on the literature, and which are of relevance not only to current IP networks, but also to future Internet architectures.

Current IP networks were not designed with energy issues in mind, and hence traditionally they have been designed for minimal investment and operational cost at maximum throughput. The challenge behind a smart energy management system is to reduce the network energy consumption with a minimal negative impact in its throughput performance. 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.

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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 [3], it will be possible to greatly reduce the energy consumption when they are idle or underused.

This paper aims therefore not only to provide an overview of energy issues and energy saving solutions that are of relevance not only to the current Internet architecture, but also to identify the contribution of the different proposals for the future Internet architecture. First we review the main proposals designed to improve the Internet architecture. Some of them will choose to use the "Clean Slate Design" and others will only try to improve existing technologies. We will then discuss techniques to make the Internet architecture more "green", i.e. to make the Internet more energy efficient. Finally, we present survey conclusions.

II. Technologies for the Future Internet

Despite the tremendous success of the Internet, its current architecture may not be the ideal solution for several challenges, such as: 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 fiber optics and radio transmissions [5]. As a consequence of the aforementioned problems, new solutions and even different paradigms being researched to mitigate them will be surveyed.

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,

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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 [9].

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 [10].

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 endpoints 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 communication delay increases [11].

The Internet architecture needs to be greatly enhanced to allow the emergence of new services and applications. The reviewed proposals try to outcome the major concerns about the current Internet architecture.

In Table I it is presented a summary of the issues addressed by each proposal.

TABLE I: FUTURE INTERNET PROPOSALS COMPARISON.

Proposal	Clean Slate	Congestion	Mobility	Routing	Scalability	Security
4WARD	✓	✓	✓	✓	✓	✓
ANA	✓	✗	✓	✓	✓	✓
FARA	✗	✗	✓	✓	✗	✗
NIRA	✗	✗	✗	✓	✗	✗
PSIRP	✓	✓	✓	✓	✓	✓
XCP	✗	✓	✗	✗	✗	✗

III. 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 [12], [13].

Only nowadays the energy consumption has become a priority problem to be solved in future Internet architectures, due to the rapid growth of energy, costs, costumers, broadband accesses and other services offered by the ISPs.

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 [14]. Next it will be discussed some of the prior work in the energy efficiency field for the future Internet architectures.

A. 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 [13]:

• Energy Saving Mode: The idea is to put equipment to sleep, since there is no need to waste energy when the equipment is not actually being used. This way it is a good energy saving mechanism to put equipment to sleep when they are idle. 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 equipment 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 way the equipment has the ability to dynamically reduce the link rate, because of lack of utilization, a technique that is being adopted by IEEE Energy

Efficient Ethernet (EEE) [15].

• 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 reducing the energy consumption. The design of new architectures and protocols must satisfy capacity needs for different network users. 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 [13].

• Reliability and energy consumption: In [16] it is explored the relationship between reliability and energy consumption. It is defined a tradeoff model between power utilization and performance of the network. In this case reliability and power saving are deeply addressed in this model, with the goal of developing robust and energy efficient networks.

• Optical technology: Nowadays, the optical technology is widely used in the backbone of the ISPs networks. The developments in this kind of technology, will lead to all-optical networks that will eliminate the need of optical converters, resulting in overall reduction of the energy consumption [17].

• Advanced CMOS technology and superconductors: another approach is to develop smaller chips that consume less energy, using CMOS technology and superconductors, achieving gains on energy consumption by around 40% [18].

B. Virtualization

The traditional paradigm used by ISPs is to run a single application in one server, due to simplicity reasons, resulting in high resource waste and consequently a lot of energy waste. Using virtualization it is possible to run multiple applications in a smaller number of machines, reducing the necessary hardware to execute those applications. The less hardware used, less energy will be required to operate that hardware.

Virtualization may be used not only in the server point of view, but also at other levels such as storage, network, platform, application and resource. For instance using server virtualization, the physical server will be separated into multiple virtual servers. This can be achieved using different approaches, such as: Virtual Machine (VM); Paravirtualization or Operating System Virtualization [13].

When using VM or full virtualization technology, multiple VMs will share the same physical machine, called host machine. It is the host operating system or VM monitor that is responsible to allocate the necessary resources for running the VMs. Each VM runs its services on top of a guest operating system, which provides the necessary abstractions for file access and network support for their running applications. This way a VM system may run different VMs with different operating systems, giving the users the flexibility to create, copy, save, read, modify, share, migrate and even roll back execution state of the VM [19]. For instance the possibility of replicating the same VM image in different hosts in an easy way makes the life for system administrators a lot easier.

The paravirtualization technology is used to reduce the performance issues of the full virtualization, since it does not replicate entirely the original guest running environment. In this case the guest operating system must be modified to be able to run in the paravirtualized environment, redirecting all virtualization-sensitive operations to the VM monitor [20]. There is a frontend driver that handles all the guests i/o requests and delivers them to the backend driver, which will interpret these requests and makes a correspondence with the desired physical device [21].

The Operating System Virtualization consists on a single operating system kernel running on a server. All guest environments can solely use this specific operating system. On the other hand the networking virtualization uses all available resources and functionalities, combining them into a virtual network or even sub dividing them into virtual networks. This allows optimize the resource utilization of network equipment in order to reduce their energy consumption.

The use of virtualization in future Internet architectures can play a big role in the energy saving field. There is still the need to evaluate which type of virtualization will allow a better energy management [13].

C. Pipeline Forwarding

The pipeline forwarding mechanism is a packet-scheduling technique that combines simplicity and effectiveness using a global Common Time Reference (CTR), in order to perform network traffic shaping. It does not need a large amount of network resources and offers good performance. It is also capable of offering QoS and good scalability [22], [23]. The pipeline forwarding is used in some architectures, which are designed to reduce the overall network energy consumption in the future Internet, e.g. the Greener Internet proposed in [12].

Using this technique, switches will be synchronized through the utilization of a time period, Time Frame (TF), which can be assumed as a sort of virtual container for IP packets. The duration of the TF can be obtained by using external sources, e.g. get the Universal Time Coordinated (UTC) from GPS or Galileo positioning systems, or it can also be distributed throughout the network. To allow QoS, the transmission capacity can be partially or totally allocated to one or more flows during the resource allocation period [12]. The pipeline forwarding behavior is managed by two simple rules:

1) The packets that will be sent in TF t by some node n, must be put in their output ports buffer in TF $t-1$.
2) When a packet p is transmitted in the TF t by a node n, it must be also transmitted by the node $n + 1$ in TF $t + d_p$, where d_p is the forwarding delay.

The forwarding delay is calculated during the resource allocation period, which involves scheduling techniques. The pipeline forwarding uses a predefine schedule, Synchronous Virtual Pipe (SVP), for forwarding a pre-allocated number of bytes during one or more TFs along a path of subsequent UTC based switches [12]. There are two main implementations of the pipeline forwarding [12]:

• Time-driven switching: Using this technique all the packets belonging to the same TF will be switched to the same output port. Therefore, it will not be necessary to perform header processing, resulting in low complexity and possible optical implementation.

• Time-driven priority: This technique is suitable for optical backbones, arranging the traffic in large capacity SVPs that are handled by high-speed switches. If more flexibility is necessary, the time-driven priority will combine pipeline forwarding with IP routing. This way, packets that enter in the same switch input port during the same TF can be sent to different output ports, according to the established rules in the IP routing.

D. Selectively Connected End Systems

Selectively connected end systems can manage their own network connectivity in response to internal or external events. This way it is possible for them to predict changes in connectivity, and reacting in accordance. For example, the end systems may predict the loss of connectivity just by knowing that they are moving to an area that has low layer-two connectivity. So, using selective connectivity will allow hosts to go to sleep, achieving a substantial power saving without sacrificing their place in the network.

In terms of power management the end system may have three different states, which are: on, off and sleep. Analogously to networking, end systems will be characterized by having connectivity, no connectivity or operating in selectively connected mode. The end system can enter in the sleep state without loosing its place in the network. Occasionally, it may be required that an end system in the sleep state to go back on, in order to perform some specific tasks. The architectural concepts and components of this solution are as follows [24]:

• Assistants: An assistant is a generic mechanism which helps the host while he is in sleep mode, by performing the routine operations that normally are assigned to end systems. For instance the assistant will allow the host to keep his connectivity by responding to keep-alive messages on his behalf.

• Exposing Selective Connectivity: For reasons concerning energy management, it is important for end systems to know each other state, and hence for the host to expose his level of connectivity throughout the different layers of his protocol stack and to inform possible peers with which he may want to communicate. For example, an active end system may be induced to enter in sleep mode when he wants to communicate with a sleeping end system.

• Evolving Soft State: There is the need to evolve soft state, since it is difficult to renew the state for sleeping end systems.

There are two solutions for resolving this problem, which are:

- Proxyable State - Using this state it will be the assistant who will be responsible for managing the soft state.
- Limbo State - This state is in the middle between soft state and statelessness. Soft state assumes that a host is not available, but there is the need to know if the host is completely turned off or only sleeping. This way when the renovation of the state expires, the host will enter in the limbo state allowing only the necessary information, used for distinguishing the two states, to be exchanged among the participants.

• Host-based Control: The end system has control of how the other ones in the network will react to his selective connectivity. Whenever a host moves to the selective connected mode it is necessary to delegate his tasks to the other participants.

E. Ranking Network Elements

In order to efficiently choose which network elements to be turned off, it is important to rank each one according to its importance 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; Betweeness centrality; Closeness centrality; Eigenvector centrality. The Degree centrality is defined as the number of links connected to each node. The Betweenness centrality represents the number of shortest paths in which a node participates. The Closeness centrality gives the average distance between a node and all the other ones, in which the more critical nodes are the ones with the lowest closeness centrality. Lastly, the Eigenvector centrality corresponds to the influence of a node in the network by taking into account the importance level of its neighbors [25].

The traffic volume based rankings solely takes into consideration the amount of traffic that is routed by the network elements. An example of the application of this principle is presented in [26]. Table II presents a summary of the characteristics of the different rankings that were described.

TABLE II: SUMMARY OF THE DIFFERENT TYPES OF RANKINGS.

Ranking	Topology Aware	Traffic Aware
Degree Centrality	✓	✗
Betweenness Centrality	✓	✗
Closeness Centrality	✓	✗
Eigenvector Centrality	✓	✗
Load	✗	✓

IV. ENERGY SAVING MODELS

To achieve significant reductions 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.

A. Dynamic Link Metric

The basic idea of the algorithm presented in [27] 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 is defined a threshold to avoid traffic congestion in a link by restraining the allowed amount of traffic that may pass in it. A link is considered congested whenever 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, based on the traffic load, the desired threshold and a configuration coefficient k, transferring the traffic load to most commonly used links [27]. Whenever the traffic load exceeds the threshold, the weight of the link will be raised in order to reduce its traffic load. When the traffic load is below the threshold, the weight of the link will be decreased in order to increase its traffic load. In this case, it will only be decreased the weight of the link with the higher utilization. The changes made to the weight of the links must be communicated to all nodes in the network topology. Finally, to power off a link it must be taken into account if the link has no traffic load and if the network remains fully connective without the link.

This approach explores the redundancy in the core networks to encounter the minimum set of links that need to be power on in order to successfully route all the traffic, allowing a reduction in energy consumption by powering-off the unused links. The downside of this approach is the decrease of network performance, especially in high-peak traffic hours, due to the increase of the packet delay.

B. Green Open Shortest Path First Protocol

In [28] it is proposed a solution that uses the topological information advertised by routers using the Open Shortest Path First (OSPF) protocol. The focus of this study is on making the OSPF protocol more "green", i.e. energy aware. The OSPF protocol specifies that each router compute its own Shortest Path Tree (SPT) by applying the Dijkstra algorithm. Hence only the links that belong to at least one SPT will be used to route data in the network.

The algorithm proposed in [28], Energy-Aware Routing (EAR), defines two sets of routers, the exporters and the importers. The exporters are responsible for computing the shortest routing paths and the importers will then compute their own SPTs based on the SPTs calculated by the exporters, selecting the routing paths to be used. This way it will be possible to reduce the number of links used for routing traffic.

The EAR algorithm is composed of three phases, which are:

• Exporter Router (ER) selection: ERs will be responsible for computing their SPT by applying the Dijkstra algorithm. The neighbors, Importer Routers (IRs), of the selected ERs will use these SPTs to identify possible links that can be switched off. The selection of the ERs is based on the information contained in the LSA database of each router. With this information the routers with the highest degree will be selected. Only routers, which are not neighbors of another ER can be selected.

• Modified Path Tree (MPT) evaluation: In this phase it will be determined the links to be switched off, according to the MPTs computed by the IRs. The IRs will use a modified version of the Dijkstra algorithm, in which the root node will be his associated ER, instead of the node itself. The SPT computed by the IR will be the same as the one computed by his ER. After this the IR will insert itself as root in the computed routing tree, creating a new routing tree called Modified Path Tree (MPT).

• Routing path optimization: After the completion of phase 2, each IR will have a list of links to be switched off. Turning off these links will generate a new network topology, which must be propagated to all network nodes. So the IRs with at least one link to be switch off must send LSA messages to the network. At the end of this procedure each network router will have the current information about the network topology.

The EAR algorithm is a solution that addresses the problem of energy efficiency in today's IP networks without taking into account QoS constraints. The main advantage of EAR is the full compatibility with the OSPF protocol, allowing energy to be saved in low traffic periods. It is still being researched the best criteria for the selection of the exporter routers and its respective number to avoid network congestion, especially in high-peak traffic hours. Hence it is possible to extend this algorithm to take into account the QoS constraints.

C. Sleep Coordination in Wired Core Networks

In [29] it is proposed a distributed routing protocol, General Distributed Routing Protocol for Power Saving (GDRP-PS), in which the goal is to put routers into sleep mode without compromising the QoS and network connectivity. This protocol will offer similar operation as other distributed routing protocols in high traffic hours, and in low traffic hours it will put some routers into sleep mode to save energy, taking into account network connectivity and QoS.

This protocol uses two types of routers: power saving routers (PSRs), and traditional routers. The traditional routers will use the OSPF protocol. These types of routers are always powered on, even when no packets are to be processed. Instead, the PSRs will have two different states: working and sleeping.

The algorithm starts by randomly choosing one coordinator, which will record the information about available PSRs and will also be responsible for coordinating the operations of the PSRs. Due to the constant monitoring of the PSRs, the coordinator will never be put to sleep. Furthermore, after a predefined period of time a new coordinator will be randomly chosen, giving the opportunity for all the PSRs to be coordinators (fairness).

To change from the working state to the sleeping state, the PSR must detect that the network is idle by measuring the maximum utilization of all the links that are connected to it, U_{max}. A network is considered to be idle if U_{max} is below a determined threshold, T_1. If the network is idle then the PSR will verify if the network connectivity can be maintained in his absence. If so, the PSR will recompute his routing table and will send a message to the coordinator to get permission for entering in the sleeping state, since it is not allowed more than one PSR in the sleep state. This is necessary to guarantee that the remaining PSRs will not be overloaded. In case of a positive response from the coordinator, the PSR will broadcast the rebuilt routing table and will enter the sleeping state for a period of time. If not, it will remain in the working state.

After waking up from the sleeping period, the PSR will rejoin the network by using the existing routing protocol and the routing tables of all the network nodes will be rebuilt. When the coordinator gets aware of the waking up of the PSR, it will verify if its own maximum link utilization is greater than the threshold, i.e. the network loading is high (high-peek hours). If so, the coordinator will send a wakeup message to the PSR, otherwise it will do nothing. The PSR is expecting a confirmation message from the coordinator in a certain period of time. If it receives the confirmation message the PSR will remain in the working state, otherwise it will go back to the sleeping state for another period of time.

In this protocol it was defined the process of putting routers in sleep mode to achieve energy savings. According to the results presented in [29], the GDRP-PS is able to achieve a reduction of approximately 18% in the total energy consumption of the network.

D. Switching off Network Elements

In [26] 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. Hereafter it will be explained the proposed heuristics to solve the aforementioned energy consumption problem, taking into account the parameters described in Table III.

TABLE III: PARAMETERS USED IN THE PROBLEM FORMULATION, ACCORDING TO [26].

Parameter	Description
x_{ij}	Link ij is on or off
y_i	Node i is on or off
$\mathcal{PL}_{ij}$	Power consumption of the link ij
$\mathcal{PN}_i$	Power consumption of the node i
f_{ij}^{sd}	Traffic from source to destination that is routed through the link ij
f_{ij}	Total amount of traffic that is routed through the link ij
t_{sd}	Average amount of traffic going from source to destination
c_{ij}	Capacity the link ij

To reduce the total network energy consumption, the solution discovers the routers and links that can be turned off without jeopardizing the network connectivity. It is assumed a complete knowledge of the network topology and of the average amount of traffic that is exchanged between all node pairs, and it is enforced some flow conservation constraints.

The proposed algorithm will iteratively try to switch off a network element (node or link). At each iteration, the network element will be disabled and all the shortest paths will be recomputed. After this step, it will be verified if the network remains its connectivity and that the traffic demand can be satisfied.

E. Dijkstra-Based Power-Aware Routing Algorithm (DPRA)

The DPRA [30] is an heuristic algorithm that consists in the partitioning of the traffic demand, from a source node to a destination node. Then it will be computed the path that consumes the minimum power for the specified traffic demand, taking into account the resources that are already allocated. This will be executed for all node pairs and until all the traffic demand is allocated.

Each link of the network will be associated with a cost equal to the increase of the power consumption of the destination node, which can be calculated taking into account the traffic of the link and the energy profile of the destination node. Afterwards, it will be calculated the maximum resources in use by each node and consequently by each link, excluding the nodes and links whose available resources are not enough for the allocation of more traffic. Finally, the Dijkstra algorithm will be executed taking into account the newly calculated costs and the disabled network elements.

F. Green-Game

Green-Game [25] proposes a model 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 awareness and topology awareness. 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.

The ranking of each node will be obtained by computing the Shapley Value [31]. The Shapley Value will rank nodes with a higher value when their absence disconnects the network and when their presence its very important in the packet forwarding process. In combination with the traffic load, the Shapley Value can efficiently distinguish the network nodes by their importance. Hence the network nodes with the lowest Shapley Value will be possibly turned off.

The high complexity in the computation of the Shapley Value makes it unsuitable for being applied in real networks. This way, in the Green-Game was proposed some optimizations to reduce the computation complexity of the Shapley Value, so it can become practical in real networks.

The work developed in the Green-Game provides an efficient way of choosing which network elements to be turned off. The higher ranked network elements will most likely be the most used ones. By using this measure it will be possible to reduce the impact of the energy saving mechanism in the network performance.

G. Summary

The reviewed energy saving models provide a mechanism that can put network elements in a power saving mode. Table IV presents a summary of the main characteristics, for each energy saving model.

TABLE IV: ENERGY SAVING MODELS SUMMARY

Energy Saving Model	Link Control	Node Control	Offline Scheme
Dynamic Link Metric	✓	✗	✗
Green OSPF	✓	✗	✗
GDRP-PS	✗	✓	✗
Switching Off Network Elements	✓	✓	✓
DPRA	✓	✓	✓
Green-Game	✓	✓	✗

H. Integrated Approach for IP and Future Internet

We have recently developed a new energy saving architecture for two different scenarios: current IP networks and a future Internet architecture (PSIRP), 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, and by integrating several energy saving techniques together, as previously described in this paper. The solution 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 offer 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. It is also proposed a ranking mechanism that classifies the importance of a network element. This mechanism is vital to achieve a good tradeoff between energy savings and network performance, mainly because it turns off in first place the network elements that have a smaller impact on the packet delivery process.

The architecture was extensively evaluated for both Internet architectures, using the NS3 simulator. Experimental 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.

V. Conclusions

The current Internet infrastructure consumes large amounts of energy because the network elements are always working at their full capacity even with a low traffic demand. This waste of energy (by the Internet infrastructures) can be reduced, by allowing some network elements to enter into energy saving modes. However, it may lead to a network performance decrease.

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. This paper presented a survey on current energy issues and energy saving algorithms for telecommunication networks, which is of importance for the appropriate design of IP energy efficient networks, and also for future Internet architectures. We are also currently evaluating a system combining several of these techniques, for which experimental results indicate significant energy savings.

References

[1] A. Bianzino, C. Chaudet, D. Rossi, and J. Rougier, "A survey of green networking research," *IEEE Communications Surveys and Tutorials*, vol. 14, no. 1, pp. 3-20, 2012.

[2] Global e-Sustainability Initiative (GeSI), "Smart 2020 report: Global ICT solution case studies," Technical report, 2008.

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

[4] N. Niebert, S. Baucke, I. EI-Khayat, M. Johnsson, B. Ohlman, H. Abramowicz, K. Wuenstel, H. Woesner, J. Quittek, and L.M. Correia, "The way 4ward to the creation of a future internet," in *IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications*, PIMRC 2008.

[5] G. Tselentis, *Towards the future Internet*, pp. 91-101. IOS Press, 2009.

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

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

[8] X. Yang, D. Clark, and A. B. Nira, "A new interdomain routing architecture," *IEEE/ACM Transactions on Networking*, vol. 15, no. 4, Aug 2007.

[9] P. Jokela, A. Zahemszky, C. Rothenberg, S. Arianfar, and P. Nikander, Lipsin, "Line speed publish/subscribe inter-networking," *ACM SIGCOMM Computer Communication Review*, vol. 39, no. 4, pp.195–206, August 2009.

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

[11] Y. Zhang and T. Henderson. "An implementation and experimental study of the explicit control protocol (xcp)," in *Proc. 24th Annual Joint Conference of the IEEE Computer and Communications Societies*, Proceedings IEEE, vol. 2, pp. 1037-1048. INFOCOM 2005.

[12] M. Baldi and Y. Ofek. "Time for a 'Greener' Internet," presented at the 1st International Workshop on Green Communications (GreenComm'09), in conjunction with the IEEE International Conference on Communications, June 2009.

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

[14] R. Bolla, R. Bruschi, F. Davoli *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.

[15] C. Gunaratne, K. Christensen, B. Nordman *et al.*, "Reducing the energy consumption of Ethernet with adaptive link rate (alr)," *IEEE Transactions on Computers*, vol. 57, no. 4, April 2008.

[16] B. Sanso` and H. Mellah, "On reliability, performance and Internet power consumption," presented at 7th International Workshop on Design of Reliable Communication Networks, DRCN, 2009.

[17] A. Gladisch, C. Lange, and R. Leppla. "Power efficiency of optical versus electronic access networks," in *Proc. 34th European Conference on Optical Communication (ECOC)*, pp. 1-4, September 2008.

[18] G. Papadimitriou, C. Papazoglou, and A. Pomportsis, "Optical switching: Switch fabrics, techniques, and architectures," *IEEE Journal of Ligthwave Technology*, vol. 21, no. 2, February 2003.

[19] Y. Li, W. Li, and C. Jiang, "A survey of virtual machine system: Current technology and future trends," in *Proc. 3rd International Symposium on Electronic Commerce and Security (ISECS)*, 2010.

[20] M. Anisetti, V. Bellandi, A. Colombo, M. Cremonini, E. Damiani, F. Frati, J. Hounsou, and D. Rebeccani, "Learning computer networking on open paravirtual laboratories," *IEEE Transactions on Education*, vol. 50, no. 4, November 2007.

[21] B. Zhang, X. Wang, R. Lai, L. Yang, Y. Luo, X. Li, and Z. Wang, "A survey on i/o virtualization and optimization," in *Proc. 5th Annual China Grid Conference (ChinaGrid)*, 2010.

[22] M. Baldi and G. Marchetto, "Pipeline forwarding of packets based on a low-accuracy network - distributed common time reference," *IEEE/ACM Transactions on Networking*, vol. 17, no. 9, December 2009.

[23] M. Baldi, J. Martin, E. Masala, and A. Vesco, "Quality-oriented video transmission with pipeline forwarding," *IEEE Transactions on Broadcasting*, vol. 54, no. 3, September 2008.

[24] M. Allmany, K. Christensenz, B. Nordman, and V. Paxsony, "Enabling an energy-efficient future internet through selectively connected end systems," ACM Sigcomm Hotnets, November 2007.

[25] A. P. Bianzino, C. Chaudet, D. Rossi, J. Rougier, and S. Moretti, "The green-game: Striking a balance between qos and energy saving," in *Proc. 23rd International Teletraffic Congress (ITC)*, pp. 262 –269, Sept 2011.

[26] L. Chiaraviglio, M. Mellia, and F. Neri, "Reducing power consumption in backbone networks," in *Proc. IEEE International Conference on Communications (ICC)*, pp. 1 –6, June 2009.

[27] S. Gao, J. Zhou, T. Aya, and N. Yamanaka, "Reducing network power consumption using dynamic link metric method and power off links," *IEICE Communications*, June 2009.

[28] A. Cianfrani, V. Eramo, M. Listanti, M. Marazza, and E. Vittorini, "An energy saving routing algorithm for a green ospf protocol," presented at INFOCOM IEEE Conference on Computer Communications Workshops, 2010.

[29] K. Ho and C. Cheung, "Green distributed routing protocol for sleep coordination in wired core networks," in *Proc. 6th International Conference on Networked Computing (INC)*, pp. 1–6, May 2010.

[30] R. Garroppo, S. Giordano, G. Nencioni, and M. Pagano, "Energy aware routing based on energy characterization of devices: Solutions and analysis," in *Proc. IEEE 4th International Workshop on Green Communications (GreenComm4)*, June 2011.

[31] S. Moretti and F. Patrone, "Transversality of the shapley value," *Springer TOP journal*, vol. 16, pp. 1–41, 2008.

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