Université de Lorraine
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PERCCOM Master Program

Master's Thesis in
Pervasive Computing & COMmunications
for sustainable development

Atefeh Maleki

OPTIMIZING THE ENERGY CONSUMPTION OF CORE NETWORKS WITH SOFTWARE DEFINED NETWORKS PERSPECTIVE

2017

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ABSTRACT

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The dense usage of networks in peak times forced network designers to over-provision resources to satisfy the needs during these specific times. Resources such as bandwidth, processing power, and memory are prepared oversized to handle high traffic loads, however, most of these devices are underutilized during the non-peak times and this unlocks the potential to optimize the power consumption of the resources proportionally to its actual traffic utilization. Due to the vertical integration of the control and data plane in the conventional network, managing the network is challenging. The Software Defined Networking (SDN) is a novel networking approach, which provides a programmable and logically centralized control plane, separating the network control from the forwarding devices. Thanks to the features introduced by SDN, the decisions for the network such as routing and forwarding are made globally. In this research, considering GÉANT network, we proposed a method by which we can remove up to 41% of the link during the peak time traffic and save up to 14% of the total power consumption.

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Nancy, August 2017

Atefeh Maleki

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ABBREVIATIONS AND SYMBOLS

EU	European Union
SDN	Software Defined Networking
ICT	Information and communications technology
EAR	Energy Aware Routing
ISP	Internet Service Provider
OPEX	Operating Expenses
SLA	Service Level Agreement
IPCC	Intergovernmental Panel on Climate Change
GHG	Green House Gas
EC	European Commission
NIC	Network Interface Card
QoS	Quality of Service

1 Introduction

The telecommunication sector is growing rapidly. GSMA a definitive source of data for global mobile operators, forecasts and analysis, and publisher of authoritative industry reports and research, reported that by the end of 2016, 65% of the world's population had a mobile subscription - a total of 4.8 billion unique subscribers. From the same source, it is predicted that by 2020 this trend extends up to 73% of the world's population - or 5.7 billion people [2]. Moreover, equipping devices with network connectivity is becoming ubiquitous and it is revolutionizing our society. Home appliances are following the trend to be "smart", our daily tasks are organized by smart phones and the laptops and computers can be connected to any printer around. This trend has made a significant increase in amount of traffic as [3] the global wired Internet traffic will have an increase of a factor of 16, to reach 250 Exabyte per month. To keep the pace, Internet Service Providers (ISP) have to update their infrastructure to support this growing demand by enlarging the bandwidth, capacity of routers and switches. This exponential growth increases the power consumption consequently. Studies show that Information and Communication Technology (ICT) has consumed more than 4.7% of worldwide energy [4], [5]. For instance, data centers are responsible for a significant percentage of annual power consumption by ICT sector. More precisely, the world's data centers consumed 416.2 TWh of electricity which is higher than the UK's total consumption in 2015. It is predicted that the energy consumption in the world's data centers will treble in the next decade [6]. In addition, major organization in the U.S. such as eBay, Akami, Microsoft and Google consume 0.6×10^5 MWh, 1.7×10^5 MWh, 6×10^5 MWh and 6.3×10^5 MWh annually. With this tremendous demand for telecommunication services, significant attention has been driven toward energy consumption of this sector from both economic and environmental perspective. This trend of energy consumption will affect the operating expenses (OPEX) significantly and increase the CO2 emission consequently. According to several studies [7], [8], by 2020 the emission of CO2 produced by the ICT sector could range from 2% to 10% of the total CO2 emissions.On the other hand, Figure 3 proves that network infrastructure has had a faster growth compare to other sections which requires more attention from research community.

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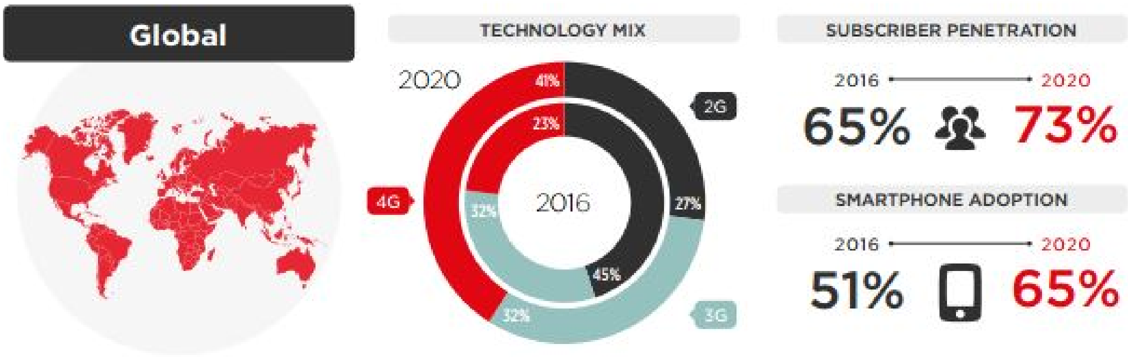

Figure 1. The subscribers penetration prediction

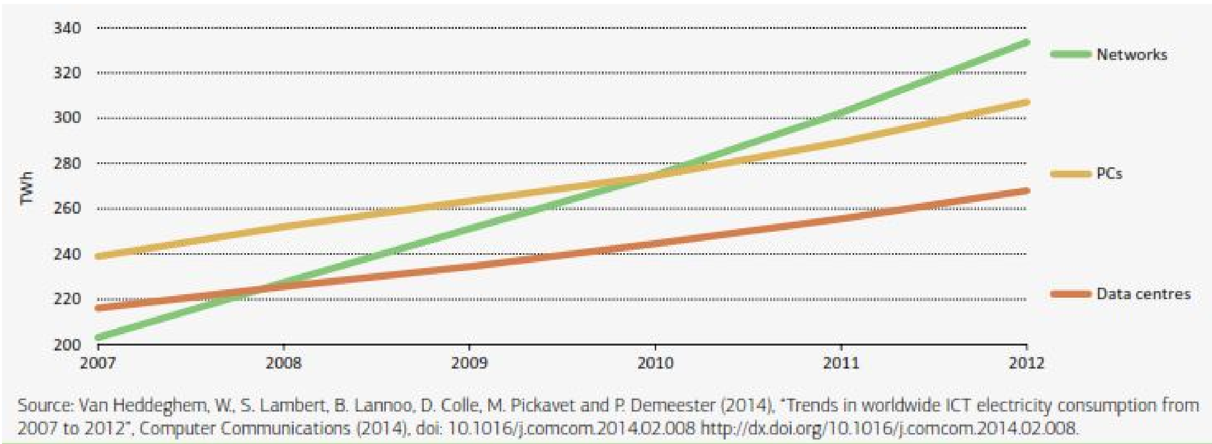

Figure 2. The traffic growth in different section of ICT

From the environmental perspective, this uprising trend is causing adverse effect on climate caused by harmful greenhouse gas emissions (GHG) [9]. The Intergovernmental Panel on Climate Change (IPCC) states that warming of the climate system is of major concerns, and is mainly due to an increase in GHG emissions from human activities. According to the Panel, warming of the climate will probably lead to extreme weather events becoming more frequent and unpredictable, and that limiting climate change will require substantial and sustained reductions of GHG emissions [10]. The negative effects of global warming have been established beyond doubt and the world is at a general consensus that we need to cut down on GHG emissions and move towards a green and sustainable future. Consequently, energy sustainability and energy efficiency are the prime goals for which research is underway in a vast areas of science. The aim is to carve out a future where technology becomes as energy efficient as possible and the energy requirements become sustainable with minimal adverse effects on climate change [11].

In this recent trend consumers expect the devices to be able to connect to the network although the main functionality remains as before. In addition, while the devices might be used only a few times in a day, they are always on and ready to serve the end-user on demand. This significant number of devices are available 24 hours a day. Consequently, they use a noticeable amount of energy that by better management can unlock the potential for saving energy. The International Energy Agency (IEA) analysis reveals that implementing best available technologies and solutions has the capacity for cutting electricity demand by more than 60% [12]. This can be achieved by better aligning the energy consumption with the actual need for performance of the service. By introducing new policies and standards for software and hardware service providers, devices could be able to go on low-power mode while they are not performing their primary function without negative impacts on delivering the desired service. Due to importance of this issue a number of projects and initiatives have been taken up by public and private organizations to introduce new standards and policies to mitigate the severe consequences of excessive energy consumption of ICT sector. In 1992 "Energy Star" [13] program was launched as an awareness program on energy efficiency and climate change by US Environmental Protection Agency. The international federation for green ICT is regulating green technology standards based professional programs called Green ICT Standard. Others include European "EARTH"(Energy Aware Radio and neTwork tecHnologies) project and "Green ICT" project, the international "Green Touch" consortium, and UK's "Green Radio" project etc. The goal of research under "Green Radio" is to secure 100x reduction in energy requirements for delivery of high data rate services, thereby reducing CO2 emissions and OPEX whilst enabling new services. "Green Touch", a Bell Labs initiative project, aims to improve the energy efficiency by transforming ICT infrastructure globally by utilizing innovative technologies. Similarly, the Green Grid association is another open industry consortium of some 200 member entities globally, that works to improve ICT resource efficiency around the world. In all such initiatives the aim is to have eco-sustainable solutions in ICT sector. In addition, the European Commission (EC) has dedicated budget for research on greening the ICT sector and set three key objectives for 2020 (which are known the "20-20-20" targets):

- A 20% reduction in EU greenhouse gas emissions from 1990 levels.
- Raising the share of EU energy consumption produced from renewable resources to 20%.
- A 20% improvement in the EU's energy efficiency.

1.1 Motivation

As mentioned earlier, the emerging demand for telecommunication services has caused an excessive increase in number of devices. Therefore, in order to guarantee the desired quality of service, reliability, and maintaining peak time traffic, the networking system is mainly designed based on over-provisioning and redundancy to assure Service Level Agreement (SLA). The switching capacity of the backbone networks is usually more than twice the peak hour traffic volumes [14]. Moreover, networks are dimensioned in a redundant manner to fulfill resiliency and fault-tolerance in case of software and hardware failure while the rest of the network is underutilized. On the other hand, the energy consumption of the devices is not proportional to the traffic loads but it grows linearly from E_0 to E_{max} [15]. Therefore, without energy consumption control policies all the equipment in the network consume energy to the maximum and consequently increase the global energy consumption of the network which is in opposition with green networking. As the traffic level in a given network follows a known daily and weekly behavior [16], there is an opportunity to adopt the utilization of the network according to the current request. For instance, Figure 3 is showing the traffic load of a data center network that is variable in different times of a day.

Management in the current network architecture is complicated as each device has a vertical integration which routing decisions are made in each single device that results in a distributed management. This heterogeneous network requires specific configurations for each device

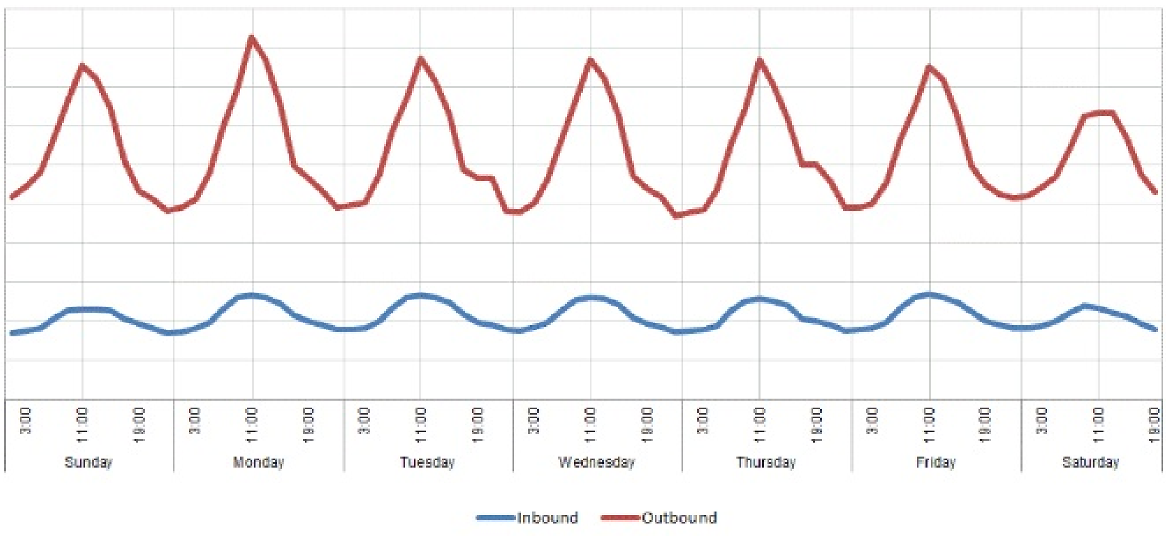

Figure 3. Traffic load of a data center network [17]

which is not easy and quick in large networks. Software Defined Networking (SDN) [18] introduces a new paradigm to overcome the limitation of the conventional network. By separating the data plane and control plane, this architecture will enable programmability, and provides central control over infrastructures, eventually, results in optimizing functionality and performance. Moreover, this will help to have an agile and dynamic network which is always ready to be changed according to the demands while the network design and architecture remains untouched. A thorough description of SDN architecture is available in the section 2.1.

1.2 Background

As mentioned above, the topic of greening the ICT sector has been an of major focus of research and several works has been done to study the possible approaches to minimize the power consumption of devices.In this section we explain the strategies for minimizing the energy consumption of ICT devices. In addition, due to concerns for an integrated management tool we study the architecture and details of SDN.

1.2.1 Software Defined Networking

The current network environment is complex as it is heterogeneous and consists of various devices. Each device is configured individually and it requires vendor-specific commands. Therefore, upgrading and updating the software and hardware need significant time and effort. Similarly, implementing a new service requires more time. As a result, the architecture remain static and slow-evolving. However, with considering the current services, the network has to be agile and respond to the needs dynamically while it is adaptive to load changes. Software Defined Network introduces a new paradigm which address these limitations by separating the network's control logic from the underlying devices. Decoupling the control plane and forwarding plane will enable programmability, and provides remote control over infrastructures, eventually results in optimizing functionality and performance. This provides a dynamic network which is always ready to be changed according to the demands while the network design and architecture remains untouched. Figure 4 demonstrates the conventional network architecture and the SDN architecture, in which the network brain is taken away from individual devices and moved to a physically or logically centralized plane. The controller applies direct control over the forwarding devices via a well-defined application programming interface (API)(e.g.,OpenFlow). This API ensures configuration and communication compatibility and interoperability among heterogeneous devices.This separation is the key to the required flexibility and facilitates control over network.

SDN architecture

An SDN architecture can be illustrated as a formation of three main layers, as shown in Figure 5. Each layer performs a specific function, application layer is communicating with the controller layer with northbound APIs and similarly the infrastructure layer is connected to the controller by southbound APIs.

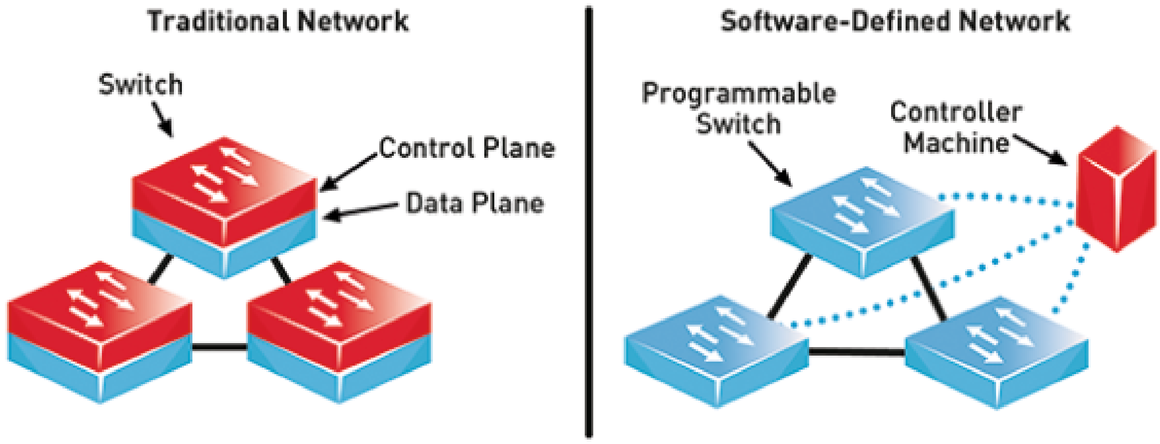

Figure 4. Simplified view of an SDN architecture vs Conventional architecture

Infrastructure layer

Compare to a traditional network, the infrastructure layer consists of the same devices such as router, switch and access point. While they are no longer responsible for making autonomous decision for routing and forwarding. These simple forwarding elements receive tasks from the above layer via southbound API. OpenFlow is the most widely accepted and used open protocol for communication between infrastructure and control plane, so far[19]. OpenFlow allows the logically centralized controller to modify the forwarding table of the switches dynamically. Each OpenFlow switch consists of flow tables, group tables, which look up the packets in their tables and OpenFlow channels which connect to an external controller. Each flow table contains a set of flow entries and each flow entry consists of match field, counter and instruction fields. When a packet matches to a flow entry in a flow table, the instruction field apply the rule on that packet. Otherwise, the packet will be act according to the rule of table-miss flow entry. It can be pipeline processing which is packet forwarding from one table to other tables until they find the matching flow. In addition the table-miss flow entry might forward the packet to the controller or drop it. The information provided by OpenFlow protocol to the controller has three main types. Event-based messages that are sent by forwarding devices to the controller when a change is triggered. Second type is flow statistics that are generated by the forwarding elements. Finally, packet-in messages from forwarding devices to controller when there is a rule for redirecting the packets to the controller.

Control layer

Control layer is the critical element in an SDN architecture which incorporates three communication interfaces, i.e. southbound, northbound and east/westbound to perform as an intermediary layer between the application layer and forwarding plane. The controller translates the required services from application layer to the forwarding devices by a network operating system (NOS). Similar to the traditional operating systems, the controller abstract the lower-level details from the upper layer along with crucial services and APIs to the developers. The controller is responsible for pushing policies to the infrastructure layer and make routing and forwarding decisions through programming. A controller might be centralized physically or to be distributed over the network. As a single controller is prone to failure, for increasing availability a cluster controller can be used instead to support more devices. Basically, the resiliency and scalability can be improved by distributed controller. On the lower level of the control layer, southbound APIs provide a common interface for the upper layer, while allowing the controller using different plugins to manage existing or new physical and virtual devices with different protocols such as SNMP,NetConf,etc.) This supports multiple protocols and device management connectors in a heterogeneous environment to communicate with the controller smoothly.

There are several controller platforms that are used in SDN environments such as OpenDayligh, Ryu, Beacon, Floodlight, Pox, Onix, HP, etc. Most of the mentioned controller only support OpenFlow as the southbound API. However, OpenDaylight, HP and Onix support a wider range of southbound APIs. Among these controllers, OpenDaylight introduces a Model Driven Service Abstraction Layer (MD-SAL), which allows several southbound protocols and plugins co-exist in the control platform.

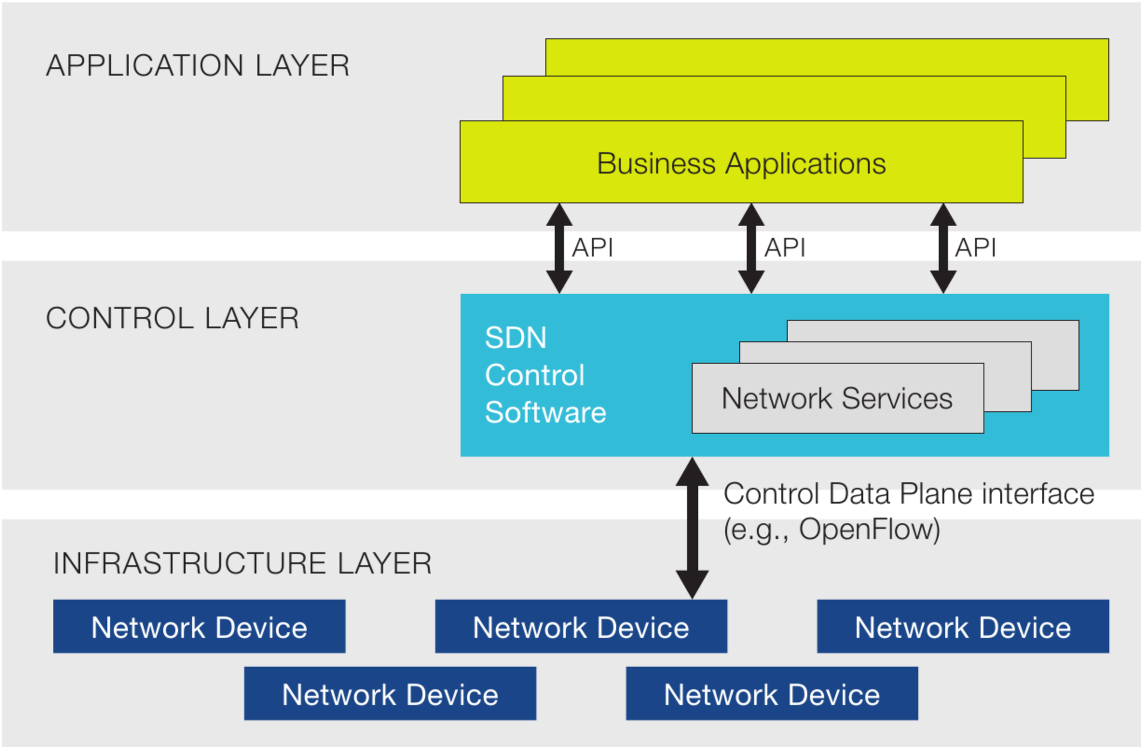

Figure 5. SDN Architecture [18]

Application layer

Network services and applications by means of northbound APIs dictate rules to the controller or receive information from the forwarding devices. For instance, the routing path is decided based on the topology input in application and the controller is meant to push the forwarding rules into the infrastructure layer. As SDN can be applied in any network environment, the possible applications covers a wide array of topics such as, routing, load balancing, security policy enforcement, and reducing power consumption.

1.3 Problem Definition

In the previous section (1.1), we covered motivations for different aspects of this research. To mentioned the main existing problems we can name over provisioning of resources for high load traffic times, which makes the infrastructure consume excessive power while they are under utilized due to non-peak times. This excessive power consumption requires attention from research community and organizations to lead the ICT toward a sustainable sector. By better management strategies and introducing standards one can unlock the potential for decreasing the energy consumption in large network architectures. However, the management in the conventional network architecture is distributed on each single device and it follows a horizontal integration. In such a heterogeneous environment, applying new strategies requires a considerable time and effort. On the other hand, engaging new technologies, such as SDN, can facilitate the management in different network architectures. Hence we can summarize the contribution of this work as follows;

- Reduce the excessive power consumption in small/large network architectures due to over provisioning for peak-time periods;
- Engaging SDN for reducing the power consumption of the network as a new paradigm for a centralized control plane.

1.4 Thesis structure

As described in the previous sections, the objective of this thesis is to evaluate the energy consumption of the network infrastructure in an SDN environment. In Chapter 2, we describe the related work in SDN and green networking, while in the chapter 3 we introduced a formulation model of our problem. In chapter 4 we proposed an energy model for the OpenFlow enabled switch,following a new approach for reducing the power consumption of the core network. We evaluate the proposed solution in GÉANT core network. In addition, the energy model formulation is evaluated in this chapter. At the end, we discussed the future work for this research.

2 Related Work

In the related work we covered the researches over green SDN. The existing approaches can be divided in two classes; Traffic aware solutions and TCAM management. In the first category, by monitoring the network, the idle devices and interfaces are detected and the traffic load will be aggregated to a subset of network. This problem is know to be an NP-hard problem, achieving the optimal solution is not possible in polynomial time. Calculating the optimized route has been focus of research in conventional network,as well. Therefore, we have covered the Energy-aware routing related researches in the following. For the second approach, the focus is on hardware components of the SDN switches.

2.1 SDN and Green Networking

Using SDN can positively affect the energy consumption of the network. As the work done in Georgia Southern University proved that using SDN architecture can decrease the energy consumption significantly [20]. In this work they compared the energy consumption of a conventional campus network and an SDN architecture. Accordingly, the results reveal that using SDN contributes to reduction of the carbon emission by 25% or more. Moreover,as SDN provides a centralized control plane over network, it opens up new opportunities for applying energy-aware solutions with profiting from its global knowledge of the network. Survey done in [21] and [22] have covered the green approaches proposed for an SDN architecture. Therefor, it needs a heuristic based solution which does not guarantee an optimal solution. However, depending on the constraints the solution can be close to optimal. In this category, constraint such as, maximum number of rules on a switch, routing policy, and the topology can affect the end result.

[23] is a continuation of Green Abstraction Layer (GAL) [24] in which the authors intended to apply GAL in SDN network. GAL is an interface defined between the controller and the

hardware which exchanges power-related data from different layers of a network component. In this research, authors have extended the Open Flow protocol to be able to convey GAL information and methods; discovery, provisioning, monitoring, commit, rollback. It means that, for example, the correct forwarding of the traffic flow can not be guarantee and one of the hops might be unavailable or on idle mode. They have emulated the environment and investigated the consumption of day-night traffic.

2.1.1 Green Networking Strategies

Gupta et al.in [25] started the first research over energy consumption of the Internet. In this research they suggested the possible methods for reducing the carbon footprint of ICT infrastructure. Authors in [26] compare the traditional and current metrics for assessing ICT performance and their effects on environment. In [27] a new approach for designing a green network architecture is introduced. Beckmann et al. [28], divided the green networking solutions into two categories; software level methods and hardware level methods. Software level solutions extend to virtualization, green TCP, and resource consolidation. While hardware solutions cover adaptive link rate, hibernation, and Energy Efficient Ethernet (EEE) etc. According to [29], authors classified the green networking techniques into four classes as described in the following.

Re-engineering

This approach is focusing on using more energy efficient hardware components for network architecture through reducing the internal complexity of elements.For routers and switches, for example, by decreasing the number of gates this can be achieved. [30] has envisioned two approaches for reducing power consumption in a network; power-aware network design and power-aware protocol design.

Interface proxying

Network devices need to be responsive to the background traffic even if they are in idle mode. And turning off the device might result in interruption in the communication. To address this issue, interface proxying was introduced. In this technique the inactive end device is switched to sleep/standby mode while the background traffic id delegated to an external entity or to a local low-energy processor of the NIC (Network Interface Card) in the same device.

Adaptive link rate (ALR)

In this approach, the Ethernet Link capacity is adapted to the local flow load. According to [31], network devices could present such a behavior if techniques like Dynamic Voltage Scaling (DVS), modular switching fabrics, etc. are applied to the devices. As today's network devices are not power proportional, authors in [32] and [33] considered several transmission rates for each link discretely and according to the traffic demand the appropriate link rate is selected.

Sleep scheduling

This method is helping unnecessary components such as nodes or links to be switched off while they are in idle mode. In this approach a new routing algorithm must be considered which is capable of aggregating the traffic load over a specific number of network components and their links, allowing the other devices to be switched off. Therefore, several research is done and this research is called energy-aware routing (EAR) [34], [29], [35], [36], [37], [30]. As the energy conservation gained by sleep-scheduling approach is significantly higher compare to power-proportional approach. [38] we decided to focus mainly on this method and we will explain it as the related work of our research.

Table 1. Green SDN approaches

Category	Protocol Name	Approach
Backbone network	[39]	Greedy algorithm
	[40]	Heuristic algorithm
	[41]	Heuristic algorithm
	STREETE [42]	By use of SPRING protocol
	BNESS [43]	Heuristic algorithm
	CWGA [44]	Two heuristic algorithms
	SENAtoR [45]	Heuristic algorithm
	[46]	Heuristic algorithm
Datacenter network	ElasticTree [47]	Greedy and Heuristic algorithm
	EXR [48]	Exclusive routing path for each flow
	RMAD+ [49]	Experimental evaluation
	PSO [50]	Swarm intelligence
	[51]	Heuristic
	[52]	Greedy algorithm
	[53]	Greedy algorithm
Campus network	AC-OFER [54]	Greedy algorithm
	[55]	Greedy algorithm
	[56]	Experimental evaluation
	[57]	Ant colony(Compared to DAPower)

2.1.2 Traffic aware routing

This approach is inspired by the traffic load pattern of the network during peak and off-peak times. The key principle in this approach is to turn on or turn off the devices while they are in idle state without compromising the Quality of Service (QoS). Moreover, in this approach the controller decides on the placement of the rules based on the network policies and end point policies. As generating these rules is an NP-hard problem [], a heuristic based solution is required. The heuristic solution does not guarantee an optimal solution, in fact they provide a solution close to optimal depending on the constraints. As each network architecture is designed for a specific purpose the approaches for saving energy might vary. For instance, in a campus network the business hours can affect the traffic load directly, while in a data center network (DCN) this might not be the case. As shown in Table 1, we have categorized these approaches in three classes, namely Traffic aware solutions for DCN, campus network and backbone networks.

Backbone network

As stated earlier, over provisioning and redundancy is adopted as a solution for fault tolerance and sustaining peak-traffic load. Similarly in backbone networks, this approach is adopted due to their critical role. The average utilization of backbone network/link is less than 30% [38], therefore, backbone networks has been focus of research for reducing their power consumption.

Authors in [58] focus on a multiple user flow data transmission in which sub flows are considered. In order to address the resource competition they introduced a virtual network architecture in which for each user flow a virtual network is designed. The problem is to find a joint route and flow allocation while considering the energy consumption of transmission devices. They formulated the joint route selection and flow allocation problem in SDN as an energy consumption minimization problem. To solve this NP-hard problem, they transform the problem into a minimum-cost commodity flow problem that can then be solved by using an N-algorithm.

In [45], the authors emphasized on reducing the consequences of turning off the unused devices. They introduced SENAtoR (Smooth ENergy Aware Routing) algorithm, which provides several features such as; tunneling for fast rerouting, smooth node disabling and detection of both traffic spikes and link failures. The algorithm works as follows. First, a pre-set tunnels are used as backup routes in case of link failure or turned off devices. Second, the SDN controller is used to suppress any incoming OSPF packet to simulate a link disconnection on the network interface to disable. As a result, OSPF nodes are forced to converge to different Shortest Path Trees (SPT). For the last step, by using SDN monitoring capabilities large unexpected traffic peaks or link failures are detected quickly.

Combining recent technologies such as segment routing (SR) with SDN can provide efficient routing. The work in [59] and [42] place a major emphasis on using SR for increasing the throughput and minimizing the rejection of the flows while reducing the utilization of network components. In both papers they proposed an algorithm with a bandwidth guarantee.

Rahnamay-naeini et al.[41] proposed a heuristic algorithm to switch off unnecessary links during low demand periods. First, K predefined paths between each pair of nodes is considered and it's sorted based on their length. Each path is comprising set of links and they are labeled by their energy costs. They also consider a traffic matrix that is variable in time. The algorithm ensures there will be at least one path between each pair of nodes. Then the second part ensures that the traffic matrix is respected and the capacity constraint of the network is satisfied. The goal of the heuristic algorithm is to find the path to keep active in order to minimize the cost of energy considering the constraints mentioned previously. All the links in the network assumed to be active and then based on their energy price, the switches are selected. The controller selects one switch in each election process. this approach continues until the point where there is no change in the status of the network.

Data center network

The network components counts for 10-20% of the total energy consumption of the data center networks [60]. The total energy consumption of networking elements was 3 billion kWh in 2006 [61]. Therefore, this section and evaluating the energy saving potential has been focus of several studies [47] . Elastictree [47] is one of the most famous works on energy savings for the network infrastructure. It utilizes the main features of SDN to make centralized decisions for forwarding and routing the flows in the network. This approach focuses on data center networks and introduce a system with three main functionality; optimizer, routing and power control. The optimizer tries to find the best subset of network to transfer the demands through the selected devices to satisfy the traffic matrix. The constraints mentioned for this work are link capacity, flow conservation and demand satisfaction. The authors developed three methods to calculate the subset with the least energy consumption; formal model, greedy bin packing, and topology-aware heuristic. As the problem requires heavy computations, the formal method is developed to evaluate the functionality of other methods according to it. Since the optimal solution is desired to find the path that consumes the minimum power while satisfies all the constraints, this problem is known to be NP-complete. Compared to other methods, the formal model is flexible to support arbitrary topology, but it can only scale up to 1000 nodes. The authors used GNU Linear Programming kit (GLPK) and CPLEX to solve the formulation. The other method to find the subset of network is Greedy Bin-Packing. This model improves the formal model's scalability. Greedy bin-packing evaluates the possible existing paths and chooses the leftmost one. As mentioned previously, the in a structured topology the paths are selected from left to right. Therefore, it results in a more evenly spread network. This approach cannot find the solution for some matrices, and for some flows a path with the lowest load is assigned. Similar to the model, this method requires to know the traffic matrix of the network, but the solution can be computed incrementally and support the on-line usage. The last method is Topology-aware Heuristic, which boosts the regularity of the fat tree topology to find the subset of network more quickly. This method does not require a full traffic matrix, on the contrary this will perform only by port counters. After finding the proper subset of network, the routing decides the path that consumes least energy, which is known to be the minimum spanning tree. In the final step, the controller manages the power state of the devices and decides to turn off the links and nodes that are unused. In order to achieve the mentioned ideas in Elastic tree, the two capabilities for gathering traffic data and applying the routing decisions are performed by OpenFlow protocol. Moreover, the NOX platform is used as the control plane to provide control and visibility over the network and each logical module is implemented as a NOX application. On the other hand, Elastic tree is not responsive to dynamic traffic and it takes the whole traffic at once while the traffic in the network is changing over time. To address this issue, authors proposed a traffic prediction model since the traffic in data center networks is following a periodic pattern. This work is a trade off between performance, robustness and energy. And with this aim they considered different aspects of the performance.

Campus network

As the campus network has a specific traffic load pattern, it has been focus of attention for researchers. The working hours in a campus network distinguishes the traffic load in day and night and even during the weekend and the devices remain idle in the mentioned periods. In addition, in this network the devices do not have a critical role and it is feasible to turn them off. Therefore, the links along with the switches are the target in this category. In [55], the authors considered a campus network with the daytime and night time working hours. In this research the routing decisions are made in the SDN controller and by monitoring the network traffic, the idle devices are detected. After aggregating the traffic to the already on devices, they switch off the remaining network components. They solved this optimization problem with a greedy heuristic algorithm. Similar works in [57] is focusing on minimizing the energy consumption of the network while they have considered the Access Points (APs) and switches for wired and wireless network. They solved the problem with Dijkstra Ant colony Power (DAPower) algorithm and evaluated their results with the similar work done before [54] based on meta heuristic ant colony algorithm. They proved that their algorithm not only outperfomrs in less power consumption but also in better network uses that includes maximum link utilization, link congestion and acceptance ratio.

2.1.3 Compacting TCAM

Most of the available OpenFlow switches have a small high-speed Ternary Content-Addressable Memory (TCAMs) which is responsible for storing the incoming rules from the controller. TCAM is very quick while it performs an entire memory search in a single clock cycle. But, they are very expensive and power hungry. the requested rules from the controller. By compacting TCAM or compressing the information stored in TCAM we can achieve a memory optimal strategy [62], [63], [64], [65].

GreenSDN [66] is the combination of all the approaches. They review the existing energy saving approaches on network infrastructures on hardware level and eventually evaluate them on a network based on SDN architecture. The paper focuses on one green capability from each layer. Adaptive Link Rate (ALR),Synchronized Coalescing (SC) and SustNMS [67]for layer one to three, respectively. GreenSDN, firstly, implements a mechanism to collect traffic statistics, then implements the power states of the devices. Finally, the green protocols are implemented. From the first layer, ALR is implemented with two predefined link rates of 10Mbps and 30 Mbps which can be choose dynamically in case of change in data rate. In the second layer SC is available by orchestrating Low Power Idle (LPI) mode of the router's interfaces and combining the outgoing packets into bursts. And finally, SustNMS is functioning in two different ways :a sustainability mode (SustNMS-S) that is maximizing the number of nodes in sleep mode by routing traffic and performance mode (SustNMS-P) that routes the network prioritizing performance. [66]

2.2 Energy-aware Routing (EAR)

In survey [68], authors have named this strategy sleep-scheduling and conducted a thorough research on the existing approaches and made a comparison. They classified this strategy according to four criteria, namely the targeted devices, distributed or central structure, traffic awareness and QoS awareness. In [69], a distributed energy-aware routing (d-EAR) algorithm is proposed and the routers are known as Exporter Routers (ER) and Importer Routers (IR). ER calculate the shortest path tree (SPT) while Importer Routers (IR) takes the SPT calculated by ER as the reference and make the modified path tree (MPT) by assuming ER as its root. The IR finds the links that need to be switched off, therefore, selection of the ER in the network can determine the number of routers to be switched off and consequently holds potential for substantial energy conservation. As the number of ERs selected will affect the network performance, this can be set based on the trade-off between the network performance and desired energy saving. d-EAR algorithm is not considering the current network traffic,which may result in overload of the remained topology. An extension of d-EAR is EAR studied in [70] which improves the ER selection procedure and maximizes the number of ER by preserving the QoS. Another energy-efficient algorithm is Energy Saving based on Occurrence of Links (ESOL) introduced in [71] which switches off the links that appeared in fewer number of SPTs. The authors have proposed four algorithms to identify these set of links. The basic-ESOL (b-ESOL) algorithm will order the links in a descending order of their occurrences in the SPTs and switches off until the network stays connected. The fast-ESOL (f-ESOL) switches off the links that has appeared in STPs less than a given threshold. The threshold value is set dynamically considering the network availability. This algorithm does not switch off those above the selected threshold although the links do not affect network connectivity, therefore, f+b-ESOL algorithm is proposed. In [72], Steiner Tree Based (STB) is an energy-aware routing algorithm that is generating a sub graph and all the links and nodes that are not in the sub graph will be switched off.

Although this approach can reduce energy consumption significantly, this trend can have disadvantages which should be considered. Firstly, "If we assume that the line cards wake up automatically on sensing data on their input ports (this is a reasonable thing to do in hardware since the logic for sensing a transmission on a line is simple and consumes little energy) then, if it takes 10μs to transition to the awake state, on a line running at 1Gbps we can expect to lose approximately 10kbit of data and to potentially add a 10μs end-to-end delay. This type of behavior is clearly not acceptable and strategies to avoid it need to be developed." Secondly, turning on and off devices might cause oscillation of devices.

This chapter introduced the related work toward the objectives of this research. A brief literature of green networking approaches. Then green networking techniques with SDN is described. Later we explained the energy aware routing approaches to get familiar with the existing researches that have been done.

3 Problem formulation

According to the optimization goal, we need to minimize the total network power consumption, while satisfying all constraints in the network. In this section we formalized the network model, introduced the constraints, and at the end, we introduced a new energy model based on an SDN switch.

3.1 Network model

A. Physical topology

We propose a model reflecting the physical topology of a network with SDN by an undirected graph $G = (V, E)$ that V is a set of nodes $i \in \{1, 2, ..., |V| = n\}$ and E is a set of links (i, j) between two nodes. For a simple graph with nodes of V, the adjacency matrix is a square V=|V|× |V| such that the element $A_(i, j) \in \{1, 0\}$ has the value of 1 when a link exists between two nodes i and j, and 0 when there is no edge between the nodes. The diagonal elements of the matrix are zero, as the edges from a vertex to itself are not allowed in simple graphs. The weight of matrix A is known as the capacity of each link and it is gathered in matrix C in which $C_(i, j)$represents the capacity of the link between node i and j.

B. Forwarding plane

The graph G represents the static part of the network, while in a network there is over provisioned resources, there might be more than one route from node i to node j. As a consequence, in an SDN network, the forwarding plane can be logically controlled and optimized by the control plane. The forwarding plane reflects the dynamic part of the network and interacts with the changing traffic.The traffic to be transmitted via network is defined by the exchange matrix

$X = |V| \times |V|$ in which the $X_(i, j) \in R+$ is equal to the flow that needs to be transported from node i to node j. $X_{i,j} = 0$ if no data has to be sent between nodes.

Each node for a common destination might have different (sub) flows. Splitting a single flow across multiple links in the topology might reduce power by improving link utilization overall, but reordered packets at the destination (resulting from varying path delays) will negatively impact TCP performance. Therefore, we discard this fact for simplicity and only the aggregated traffic will be considered.

The forwarding plane decides about the output port of each node (the next hop) based on the destination and defines the overall path $P_(i, j)$ between node i and node j (only required if only $X_{i,j} > 0$). A path is an ordered set of nodes such that $P_(i, j) \in V$ and $P_(i, j) = \{v_1, v_2, ..., v_l\}$ with $v_1 = i$, $v_l = j$ such that v_i is adjacent to $V_(i + 1)$. And the second notation of the path is introduced by $Q_(i, j) \in E$ with $Q_(i, j) = e_(v1, v2), e_(v2, v3), ..., e_(vl - 1, vl)$. To show the forwarding decisions of the nodes, the matrix $F = |V|^2 \times |V|$ is introduced such that $F_((i, j), v) = 0$,if the flow from node i to node j will not be forwarded with by the node $v \in V$,i.e. $\forall v \not\equiv j, v \notin P_(i, j)$, otherwise $F_((i, j), v)$ gives the node $v + 1$ that is the node adjacent to the node v within the path $P_(i, j)$. In other words, $F_((i, j), v) = v + 1$ that is the next hop from node v. Therefore, the path between node i and node j can be defined as follows;

$$P_(i, j) = \left\{ i, F_{(i,j),i}, F_{(i,j),F_{(i,j),i}} ..., j \right\}$$

C. Network Constraints

In a redundant topology, several paths can be designated, however, only paths satisfying the flow requirement can be chosen. Constraint (1) ensures that the capacity of the link has to be greater or equal to the flow throughput.

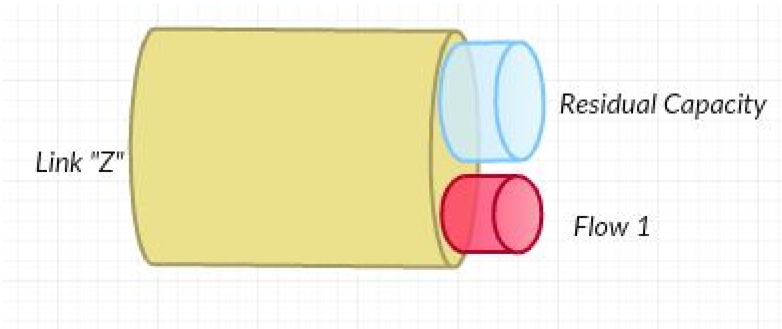

Figure 6. Link capacity

$$\forall e_{k,l} \in Q_{i,j}, C_{k,l} \geq X_{i,j} \tag{1}$$

Since a single link might be participating in different paths, the capacity of the link can be shared for different flows. Constraint (2) ensures that a path can only be a good candidate if :

$$\forall v \in P_{(i,j)}, \sum X_{k,l} \leq C(v, F_{((i,j),v)}) \tag{2}$$

The recent constraint guarantee if the residual bandwidth is sufficient for the next incoming flow. For clarification, Figure 6 illustrates a link(Z) which is used by *Flow 1*. If we want to consider the link Z for routing another flow, we need to be aware that a portion of the link capacity is occupied by other flows.

Regarding the aforementioned constraint, choose the next hop for a given path can be determined with the constraint (3) as follow;

$$\exists v' \in \left\{V - P'_{(i,j)}\right\}, C_{(V,V')} - \sum_{(k,l)\in V^2,(k,l)\neq(i,j)|F_{(k,l),v}=v'} X_{k,l} \geq X_{i,j} \tag{3}$$

Constraint (3) ensures if the residual capacity of the entire path can bear tolerate the load. Multi-commodity flow model is a classical routing problem in a network with multiple flows, which ensures the flow conservation at source, destination and in transit [12]. This is guaranteed in constraint (4).

$$\exists e_{i,j} \in Q_{sd}, \sum_{e_{i,j} \in E} e_{i,j} - \sum_{e_{i,j} \in E} e_{j,i} = \begin{cases} 1 & i = s; \\ -1 & i = d; \\ 0 & i \neq s, d. \end{cases} \tag{4}$$

Therefore, the Matrix F can be seen as the global forwarding table of the entire network.

3.2 Energy consumption model

Several researches were done to model energy consumption of the network devices. In [73], authors introduced a model for the power consumption of Ethernet switches. However, this model is specifically for Ethernet switches and cannot be used for our scenario. Therefore, we introduced a new energy model for OpenFlow enabled switch. As mentioned earlier the energy consumption of a switch is not proportional to the traffic load [15]. However, the dynamic part contributing to the power consumption of the switch is considerable. The fans, chassis, switching fabrics, etc., are considered as the fixed energy consumption of the switch, while working ports and their capacity are referred to the dynamic part. At this stage, since we want to minimize the energy consumed by the architecture, we need a model of energy consumption of each active device. The model will be used to predicate the overall consumption and optimize the forwarding table.Equation (5) describes a generic energy model.

$$\varepsilon_v = \alpha + \sum_{(i,j) incidenttov} \mu(C_{i,j}) \tag{5}$$

Where α represents the fixed energy consumption, and μ is the energy consumption of the ports considering the link capacity from matrix C (It is also important to remind here that in fact we assume also that $C_{i,j}$ = $C_{j,i}$). For example, $\mu(C_{i,j}) = \beta$ if $C_{i,j}$ = 10 or $\mu(_{Ci,j}) = \gamma$ if $C_{i,j}$ = 100. Hence, the overall energy consumption of the network can be derived from matrix A and matrix C as follows ;

$$\varepsilon_{tot} = \sum_{a_{i,j} \in A} a_{i,j}(\alpha + \sum_{(i,j) incident to v} \mu(C_{i,j})) \tag{6}$$

In this section we formalized the problem and the optimization goals of the research. A generic energy consumption model is introduced and in order to prove this model we performed several experiments on an OpenFlow switch. The next section is describing the experiment details.

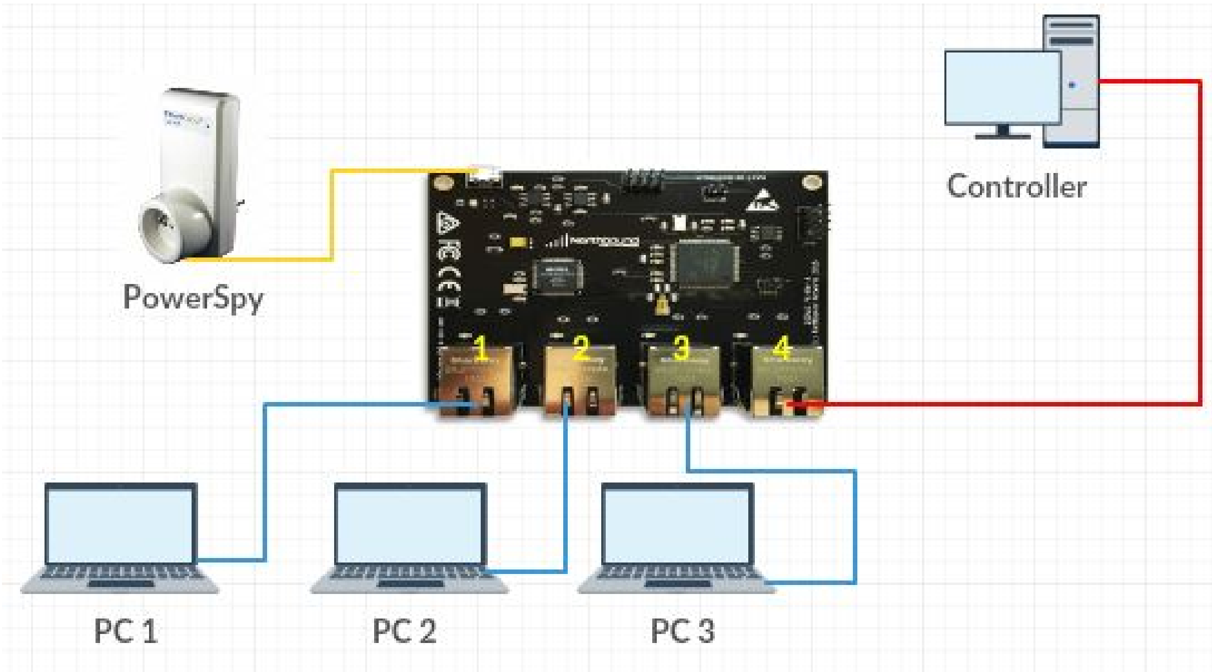

Figure 7. Experiment design

4 Implementation

In this section we implement a new energy model for the OpenFlow enabled switch (Zodiac-FX) and in the following we proposed a new approach for saving energy in core networks.

4.1 Energy model of Zodiac-FX switch

The experiment was done using the Zodiac-FX switch, a four-port open flow enabled switch which has capacity of 10/100 Mbps. The architecture is shown in Figure 7. For this experiment, we measured the energy consumption of the Zodiac-FX switch via PowerSpy2. The switch is powered through PowerSpy2 and the data of the power consumption is sent via Bluetooth to the software. The software provides real time information of the maximum and minimum power consumption along with the standard deviation and average value (Appendix 2 and 3). Each port is connected to a PC and according to the experiment we increased the number of active ports to compare the effect of used ports in the energy consumption of the switch.

As mentioned earlier, we can divide the energy consumption of network equipment into constant and dynamic part. In our case port number 4 is connected to the controller, and since SDN switch needs to communicate with the controller to receive the rules and fill the flow table, it is considered as the constant part of the energy consumption. In our scenario the number of ports and the bandwidth capacity is considered as the dynamic part.

4.2 Linear regression analysis

Linear regression is use for modeling the link between a scalar dependant y and an independent variable X. "In linear regression, the relationships are modeled using linear predictor functions whose unknown model parameters are estimated from the data. Such models are called linear models. [74].

having Y as the dependent variable or the response, and $X_1, , X_k$, as the independent variables, then linear regression analysis would be:

$$Y = c_0 + c_1X_1 + c_2X_2 + \ + c_kX_k \tag{7}$$

c_0, c_1, c_2, c_k are constant and they are distributed in a similar approach. c_0 is known as the catch of the model. It means that, c_0 is the fixed part which is the expected value of Y when all the Xs are zero or has no value. And c_i is the coefficient (multiplier) of the variable X_i. All the cs and Xs together are the overall model. Coefficients are exclusively for each X and they are not related to the others. This is about one of the simplest possible models for predicting one variable or response from a group of other variables.

Regression Equation

$$energy =$$

$$1.06433$$
$$+ 0.18011 \text{ (port } 1_{100}) + 0.17533 \text{ (port } 2_{100}) + 0.17600 \text{ (port } 3_{100})$$
$$- 0.04011 \text{ (port } 1_{10}) - 0.03100 \text{ (port } 2_{10}) - 0.03900 \text{ (port } 3_{10})$$

(8)

For Zodiac-FX we have two variables, one is the different bandwidths, which directly affects the power consumption of the switch. And the other is the number of active interfaces. To ensure the obtained results, we did 10 round of measurements for each case which is available in Appendix 1. Due to lack of flexibility to configure the speed of the ports, we had to configure the connected device on the desired speed. Therefore, thanks to the feature of "auto negotiation" the switch performs at the required speed. The results reveal that by using the links with 10 Mbps capacity the energy consumption is decreasing. Surprisingly by increasing the number of 10 Mbps interfaces, the power consumption decreases. To answer this behavior we need to consider several factors. Firstly, due to the lack of flexibility in this device it was not possible to turn off the ports. Therefore, it is not known at what speed the ports are functioning while they are not being used. As a consequence, we follow the behavior of the device at speed of 100 Mbps and leave the answer of the behavior in another research. Obviously, the power consumption of ports at speed of 100 Mbps is higher than speed of 10 Mbps. And by increasing the number of active ports at speed of 100 Mbps the overall power consumption of the switch increases consequently. Figure 8 shows the trend of increasing the number of ports in the switch for two speed of 10 Mbps and 100 Mbps.

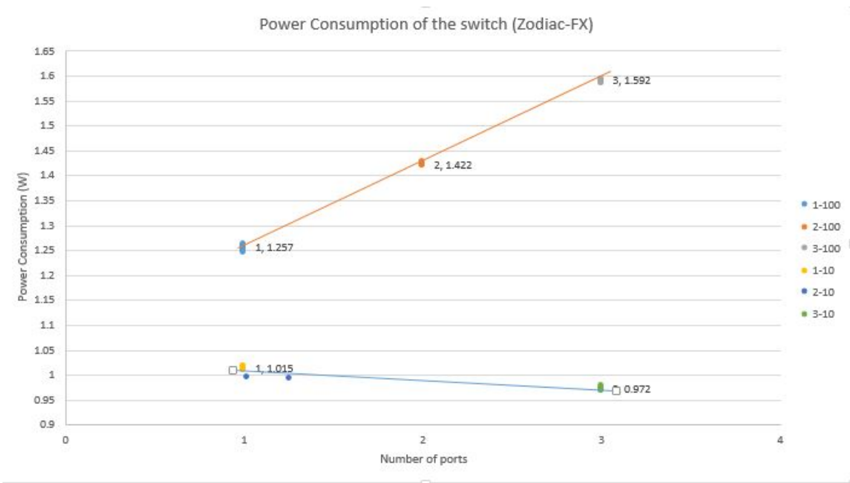

Figure 8. Linear regression of the energy consumption

In order to make the formula more simple, we took an average of three values for three ports, therefore, the simple form of formula is as follows;

$$energy = 1.06433 + 0.177(\beta) - 0.367(\alpha) \quad (9)$$

in which $\begin{cases} \alpha = \text{Number of ports with capacity of 10 Mbps} \\ \beta = \text{Number of ports with capacity of 100 Mbps} \end{cases}$

As mentioned previously this research is focusing on reducing the energy consumption of the network. With this aim we propose a method to reduce the energy consumption and we test it in a known core network-GÉANT.

4.3 GÉANT network

In this work, we evaluate the probability of saving energy in GÉANT core network from SDN perspective. GÉANT project launched in November 2000, operating the European network for research and education community. It interconnects national research and education networks (NRENs) across Europe. This project then followed by a second generation network, named GÉANT2, covering 30 national networks in 34 countries. The next GÉANT project (GN3) started in 2009 and continued for four years. The project entered its fourth phase named GN4-1 followed by a second version, GN4-2. GN4-2 is the current phase as part of the GÉANT 2020 Framework Partnership Agreement (FPA) .The main objective is to provide an innovative and stable environment for the growth of the GÉANT network, ensuring that Europe remains in the forefront of research by providing the best possible infrastructure. Currently, the GÉANT network is the largest and most advanced research and education network in the world by gathering 38 NREN partners. It is connecting over 50 million end-users at 10,000 institutions across Europe. The backbone network is operating at speeds of up to 500 Gbps and links to research network in other world regions covering over 100 national networks worldwide [75]. The latest network map of GN4-2 is shown in Figure 9. As can be seen the links are operating at mediums with capacity of 1.2 Gbps, 10 Gbps and 100 Gbps.

4.4 Methodology

We synthesize matrix X similar to the data sets available in SNDlib in [76] which represents the dynamic traffic of a subset of nodes with the granularity of 15 minutes. In this matrix all the nodes send traffic to other destinations. Figure 10 illustrates the graph of our scenario.

The method that we considered only focuses on the paths that were already used. We route the traffic by using the used path while satisfying the constraints (1), (2) and (3) mentioned in the previous section. Nevertheless, by violating any of the constraints a new path with enough

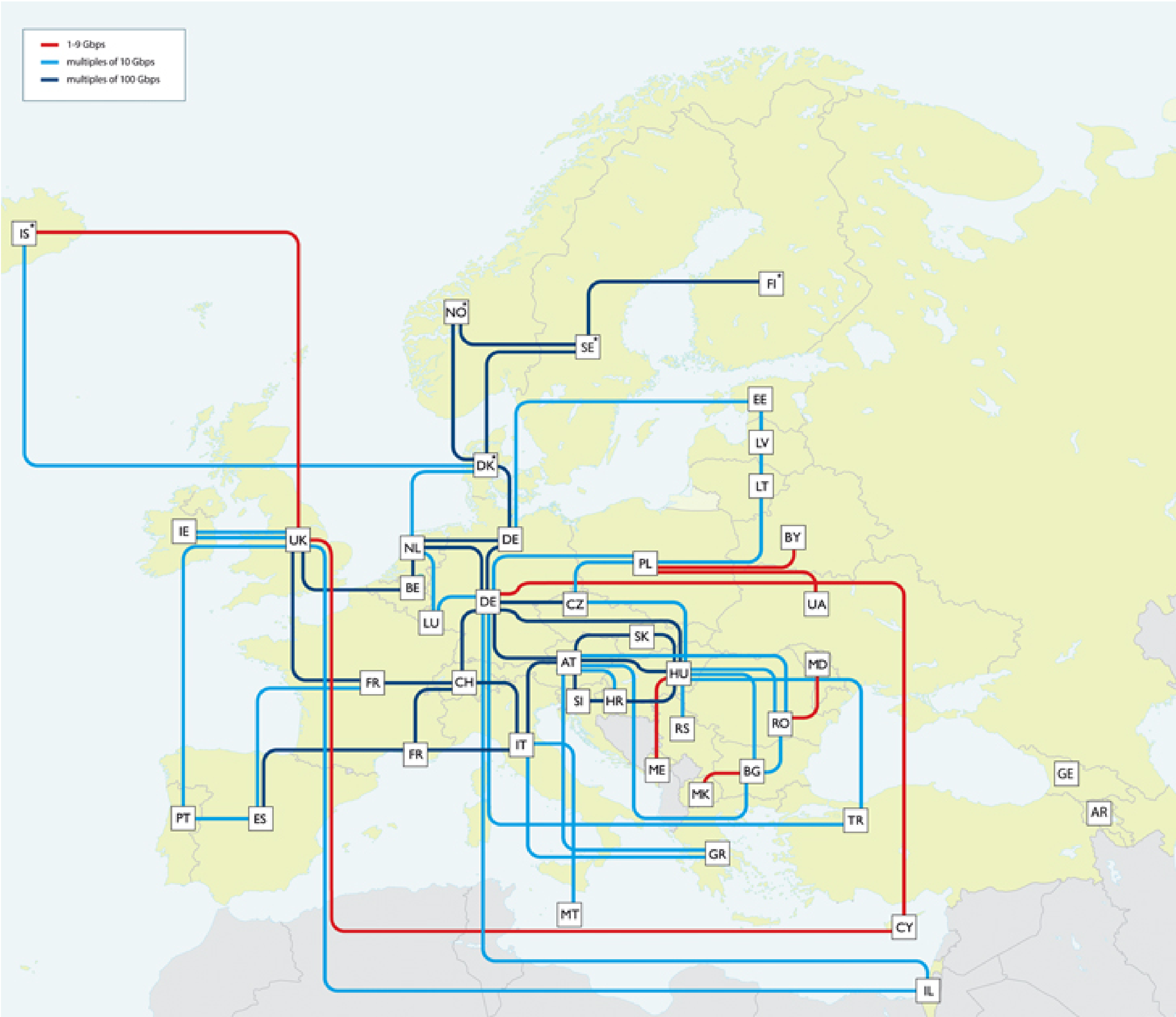

Figure 9. GÉANT map

capacity will be calculated to accommodate the flow with using the minimum number of resources. We name this approach Shared Path First (SPF). As an example, assume the first flow from AT to BE (Figure 11).

For the first flow the shortest path will be chosen similar to Figure 11. And for the next flow from AT to FR, although a shorter path through CH exists, the path from BE to FR will be chosen. Moreover, while choosing this path, the network constraints are considered. Having the first flow, traffic from AT to BE, the selected path respects the constraints. As for the first constraint, each link has the capacity higher than the size of the flow. For the second constraint, the overall path consisting of several links can accommodate the traffic. Considering the second

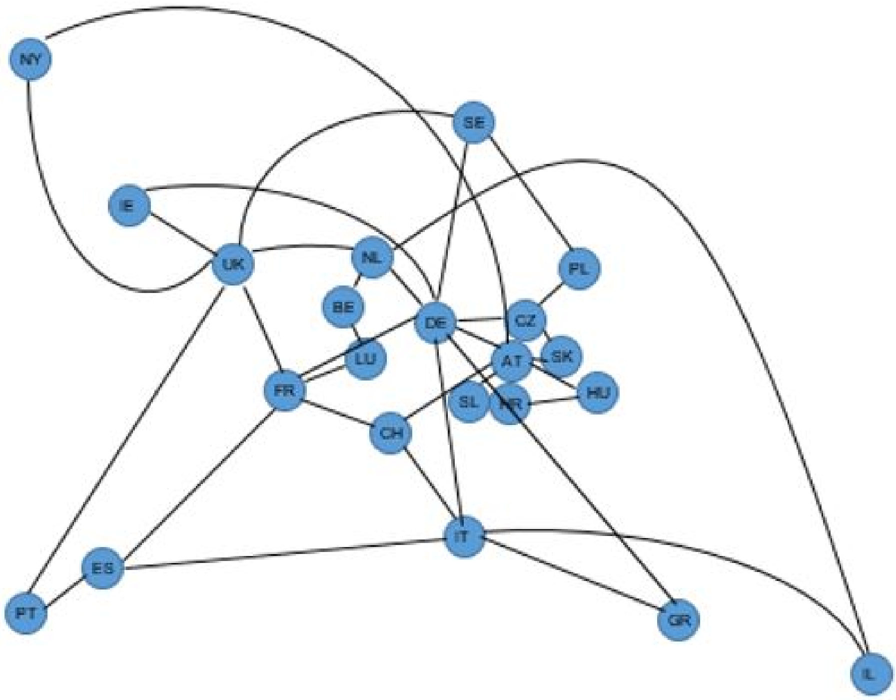

Figure 10. GÉANT graph

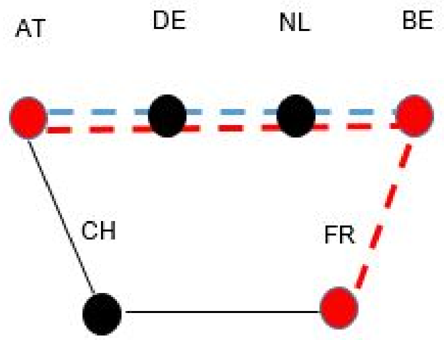

Figure 11. The traffic from AT - BE and AT - FR by using SPF
Blue lines represent the traffic from AT to BE
Red lines represent the traffic from AT to FR

flow, traffic from AT to FR, both constraint (1) and (2) are ensured. However, since the medium is used by other flows the third constraint guarantees that the shared links have enough capacity to handle the traffic. Similarly for all other flows this method is applicable.

An energy model for the device was introduced and the suggested optimizing routing algorithm was explained. In the next chapter we evaluate the energy model and the proposed energy saving approach by performing experiments.

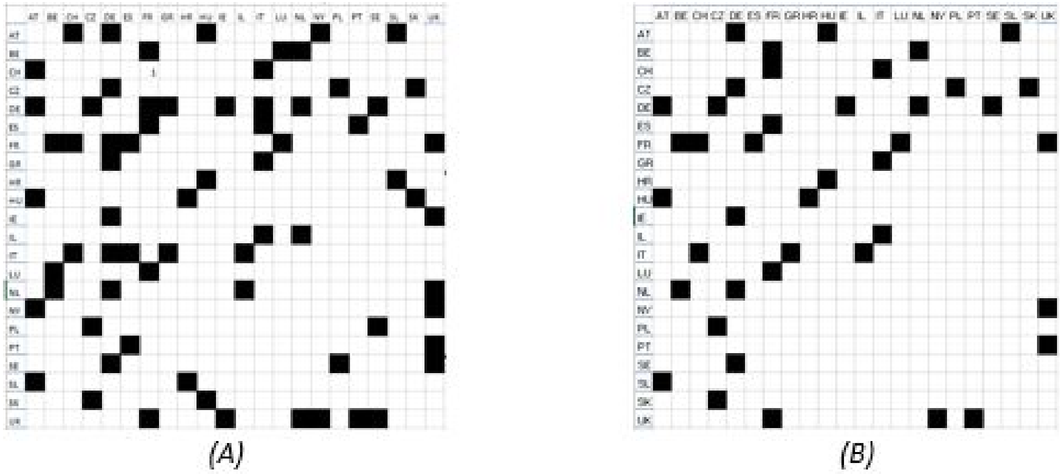

Figure 12. (A) Adjacency Matrix with Dijkstra's Algorithm
(B) Adjacency Matrix with Shared Path First

5 Evaluation and results

In this section we evaluate the proposed method for reducing the energy consumption of the network by a set of experiments, later we evaluate the energy model of the Zodiac-FX switch.

In order to evaluate the method in the GÉANT network, we considered 15 minutes of flow transmission and compared SPF with the shortest path found by Dijkstra's algorithm. According to the available data set, to find the shortest path between each pair of nodes for the required flows all the edges in the network were utilized. However, with SPF we only route the traffic by using the used path considering the constraints, otherwise, a new path with enough capacity will be generated. By applying SPF we could save up to 41% of the links compare to the shortest path approach. Figure 12 demonstrates the adjacency matrix of the two mentioned approaches. The black boxes represent the active link between two nodes. We could fulfill the constraints and successfully transfer the flows by using only 21 out of 36 links. Since all the nodes were sending traffic it was not possible to turn off any node. From each node, there is a path to other nodes that is using the shared path only.

According to the Equation (6), the energy consumption model of each device consists of a static

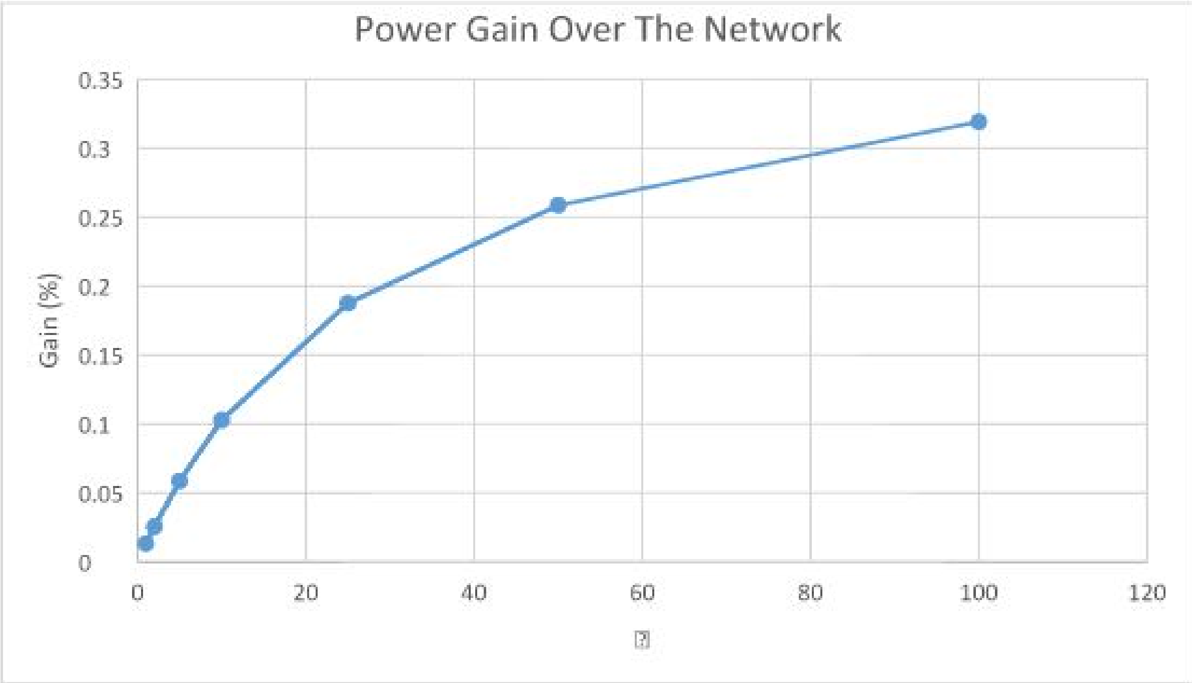

Figure 13. The power gain of the network with SPF Vs. Shortest Path

and dynamic portion. If we assume the dynamic part consumed $\rho\%$ of the static portion, the equation will be as follows;

$$\varepsilon_{tot} = \sum_{a_{i,j} \in A} a_{i,j}(\alpha + \frac{\rho}{100}\alpha) \tag{10}$$

By assuming that all the devices are using the same amount of energy, and according to Equation (8) in chapter 3 we can conclude that if the energy consumption of the dynamic part is $\rho\%$, we can gain a reduction in power consumption similar to the Figure 13. An interesting point in this diagram is that even if we consider the dynamic energy consumption of the network as 100%, the gain is not much different compared to the beginning of the graph which is more steep. Although this assumption is far from reality, this will concrete the fact that focusing on energy consumption of dynamic part can return promising results. It is crucial to mention that one link connects two switches, therefore, each link belongs to two interfaces. In another word, we can conclude that by removing one link, we save energy for two ports. Considering ρ as 10%, we can see that SPF can have a power gain of little over 10% over shortest path first.

Having the energy model for the Zodiac-FX switch in chapter 4 (Equation 8), the energy consumption of each port with capacity of 100 Mbps is 16% of the whole fixed part. This fact reveals that the dynamic part of the switch is consuming 50% of the static part. Therefore, we can observe the removing links can have a significant impact on the overall energy consumption of the network. In our scenario, removing 15 links from the topology will turn off 30 ports in the network. This will help to reduce the energy consumption of the network by 14%. It is important to mention that, the data provided by SNDlib shows that the all the links in the network are using identical capacity of 40 Gbps. Hence, we also consider the bandwidth with higher capacity for the energy model.

As we can see by comparing two different algorithms, SPF and shortest path, SPF can reduce the energy consumption of the network by up to 14%.

6 Discussion and Conclusion

6.1 Discussion

The obtained results are according to the traffic data set for peak time of the network, when all the nodes were active and sending big chunks of traffic, however, during the off-peak time of the network less links can be used. In this case, GÉANT network and in general all core networks, the probability of avoiding nodes in routing is low as each node has a critical position in the architecture and several sub nodes are connected to it. Unlike the core network architecture, the campus network architecture and other enterprise networks have a pattern of traffic load due to working hours. Therefore, reducing power consumption has a distinguishing probability by eliminating nodes and links. In data center networks, there is a high ratio of redundant paths while the energy consumption of data center networks are also very dependent on the working time. Thus our proposed method should be evaluated in different network architectures to prove that it is practical for all the network architecture. In addition, this research was done based on the SDN switch that is used for small use cases and laboratory purposes. One real device for backbone purposes can make more realistic results.

For having a fare routing for simultaneous incoming flows, several approaches can be considered, giving priority to the flows and considering an appropriate Time To Live (TTL).

Another positive point about our solution is that, for each flow request a new path is calculated, but SPF is not causing device oscillation since the new path is utilizing the previous used links. Frequent changes in the device configuration might degrade the QoS for the users.

In addition, as the core networks are wide (in our case across Europe), it is interesting to consider the energy consumption of supporting infrastructure such as repeaters and the effect of distance on energy consumption of the links. The later point, needs further research to include it in the energy model of the network as the dynamic part of energy consumption.

Different aspects of QoS of the proposed algorithm should be considered, in our case we introduced the set of constraints, however, there must be more approaches to test the congestion of the network. If the links are put in sleep mode, there should be a well defined mechanism for turning them on in case of traffic load. This transition needs to be quick so that it would be invisible from performance perspective. Optimization for wake up time of the components can be done by tunneling or segment routing to improve the QoS. In the related works [41], [47], [55], authors solved this MILP to perform their approach of power saving. For future works, we will solve the problem with a heuristic algorithm and validate the results with a simulation tool. Later it needs to be tested in an SDN platform and validate our results based on the results.

6.2 Conclusion

In the traditional network architecture redundancy and over provisioning are design techniques to ensure reliability and to improve the fault tolerance in special occasions, such as peak traffic times or in case of a hardware or software failure. This is due to vertical integration of the network while there is the absence of a global vision of the network. By SDN, however, the global view provisioned can help to make decisions dynamically and adjust the consumption of resources in accordance with the demand. In this paper, we proved that by managing the routing and forwarding decisions in a network the possibility of decreasing energy consumption is high. Specifically, in GÉANT network in peak traffic time we could save up to 41% of the links. We also formulated the energy model and introduced an energy model for the SDN switch (Zodiac-FX). According to the experiments the energy consumption of a port counts as 16% of the fixed power consumption which leads to a 14% reduction of power consumption in the whole network. Since this problem is a Mixed Integer Linear Problem (MILP), a heuristic-based algorithm can be a solution to apply our proposed method to solve the problem of routing. In the related works, authors solved this MILP to perform their approach of power saving. For the future work we solve the problem with a heuristic algorithm and validate the results with a simulation tool.

Switch D5:92			Round 1	Round 2	Round 3	Round 4	Round 5	Round 6	Round 7	Round 8	Round 9	Round 10
0	0	0	1.055	1.051	1.055	1.056	1.05	1.051	1.059	1.055	1.051	1.051
10	0	0	1.011	1.017	1.015	1.013	1.011	1.016	1.015	1.018	1.015	1.023
0	10	0	1.023	1.017	1.026	1.012	1.014	1.016	1.015	1.015	1.023	1.016
0	0	10	1.025	1.02	1.018	1.01	1.02	1.014	1.023	1.016	1.023	1.018
10	10	0	1.004	0.991	0.999	0.999	0.997	0.999	0.998	0.995	1.003	0.992
10	0	10	0.995	0.995	0.997	0.999	0.992	0.996	0.995	0.992	0.994	0.995
0	10	10	1	0.999	0.995	0.995	0.997	1.001	0.997	0.994	0.997	0.999
10	10	10	0.972	0.969	0.978	0.972	0.969	0.973	0.971	0.972	0.972	0.972
100	0	0	1.25	1.255	1.258	1.247	1.263	1.245	1.254	1.257	1.257	1.253
0	100	0	1.249	1.25	1.249	1.246	1.251	1.25	1.249	1.25	1.252	1.243
0	0	100	1.25	1.258	1.257	1.247	1.251	1.255	1.258	1.248	1.25	1.252
100	100	0	1.426	1.423	1.426	1.427	1.425	1.423	1.42	1.421	1.422	1.418
100	0	100	1.432	1.434	1.433	1.431	1.428	1.431	1.438	1.428	1.426	1.427
0	100	100	1.424	1.425	1.423	1.423	1.416	1.423	1.422	1.422	1.417	1.412
100	100	100	1.585	1.585	1.591	1.589	1.589	1.586	1.593	1.588	1.592	1.588
10	100	0	1.196	1.194	1.195	1.191	1.193	1.194	1.194	1.198	1.197	1.195
10	0	100	1.194	1.203	1.208	1.203	1.196	1.203	1.206	1.203	1.205	1.204
100	10	0	1.218	1.209	1.219	1.21	1.205	1.22	1.201	1.208	1.213	1.207
0	10	100	1.202	1.208	1.215	1.201	1.2	1.208	1.204	1.209	1.211	1.213
0	100	10	1.195	1.197	1.203	1.203	1.198	1.2	1.21	1.209	1.208	1.203
100	0	10	1.198	1.21	1.208	1.205	1.215	1.218	1.211	1.219	1.211	1.213
100	100	10	1.382	1.372	1.37	1.384	1.385	1.383	1.381	1.381	1.378	1.376
100	10	100	1.389	1.391	1.385	1.395	1.389	1.391	1.389	1.394	1.386	1.386
10	100	100	1.381	1.387	1.385	1.39	1.382	1.38	1.378	1.377	1.387	1.385
100	10	10	1.164	1.161	1.16	1.166	1.166	1.167	1.168	1.161	1.168	1.168
10	100	10	1.15	1.158	1.152	1.154	1.144	1.151	1.149	1.148	1.152	1.154
10	10	100	1.159	1.161	1.167	1.161	1.154	1.162	1.169	1.167	1.164	1.157

Figure 14. The detailed measuring power consumption of Zodiac-FX

Appendix 1

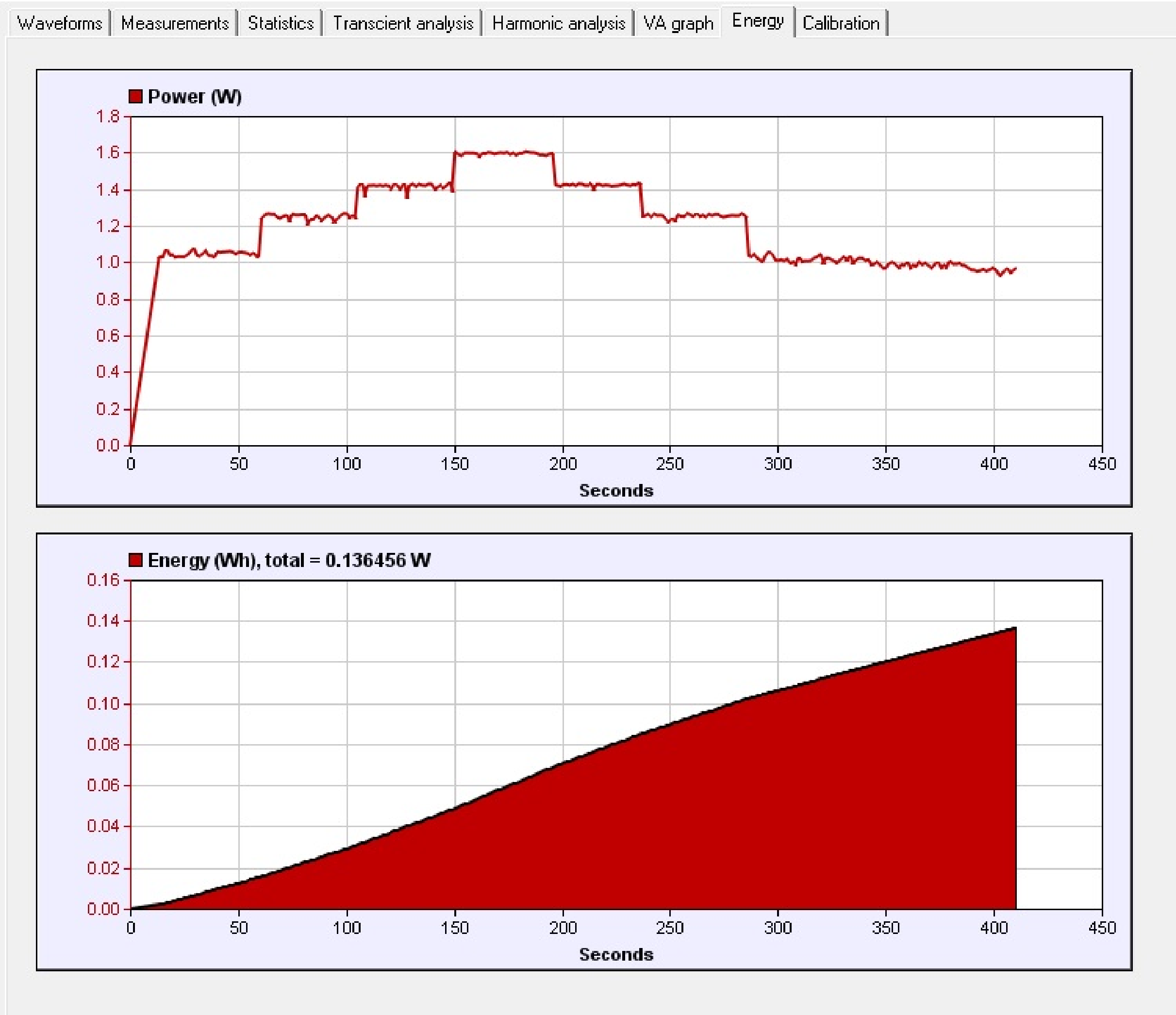

Figure 15. Real-time power measurement by PowerSpy2

Appendix 2

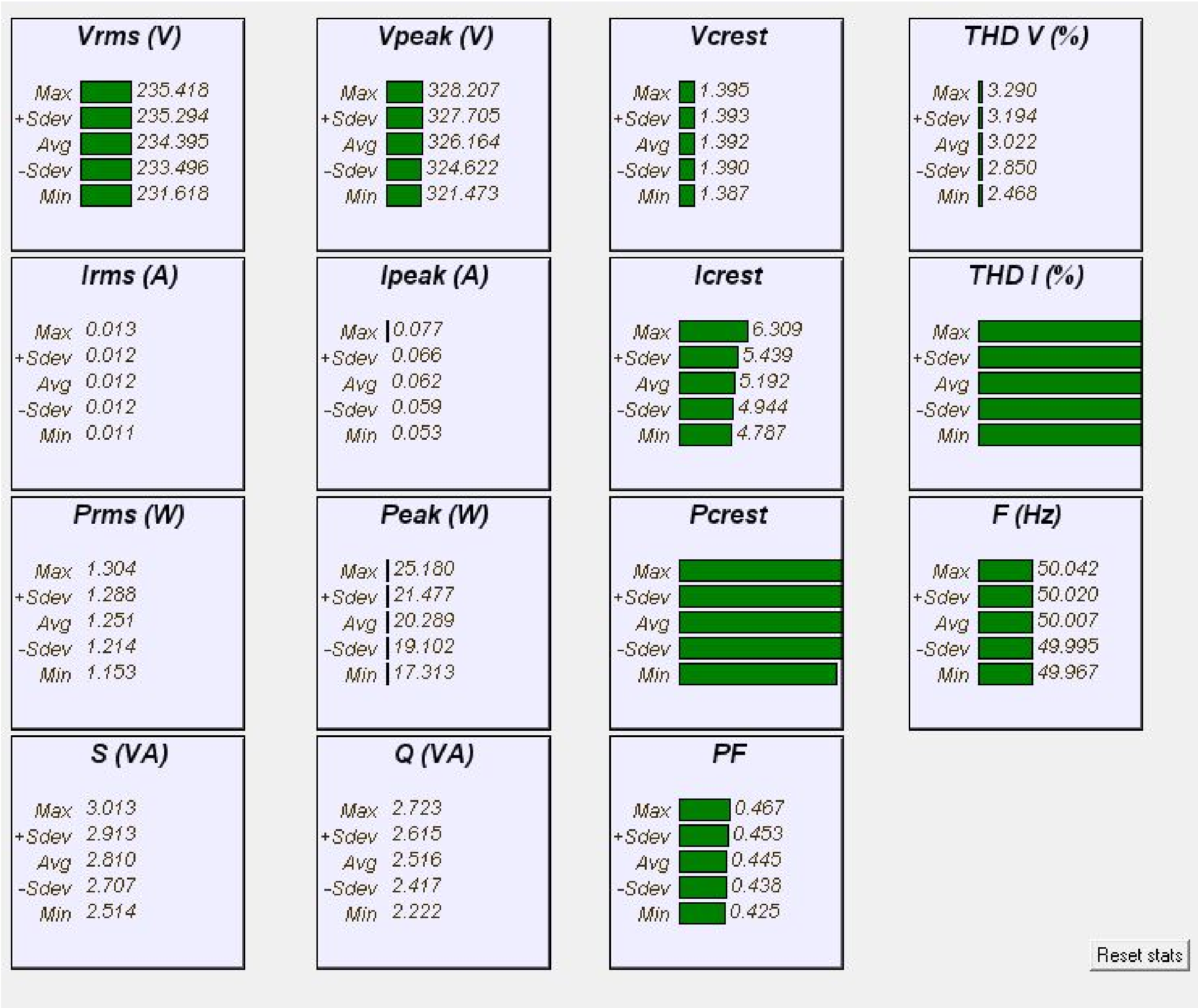

Figure 16. Real-time power measurement with maximum, minimum and standard deviation

Appendix 3

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