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Assessing the Impact of EEE Standard on Energy Consumed by Commercial Grade Network Switches

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***Abstract* —** This book chapter is adapted from [1] and it is closely linked to work published in [2] and [3]. Reducing power consumption of network equipment has been both driven by a need to reduce the ecological footprint of the cloud as well as the immense power costs of data centers. As data centers, core networks and consequently, the cloud, constantly increase in size, their power consumption should be mitigated. Ethernet, the most widely used access network still remains the biggest communication technology used in core networks and cloud infrastructures. The Energy-Efficient Ethernet or EEE standard introduced by IEEE in 2010, aims to reduce the power consumption of EEE ports by transitioning Ethernet ports into a low power mode when traffic is not present. As statistics show that the average utilization rate of ethernet links is 5 percent on desktops and 30 percent in data centers, the power saving potential of EEE could be immense. This research aims to assess the benefits of deploying EEE and create a power consumption model for network switches with and without EEE. Our measurements show that an EEE port runs at 12-15% of its total power when in low power mode. Therefore, the power savings can exceed 80% when there is no traffic. However, our measurements equally show that the power consumption of a single port represents less than 1% of the total power consumption of the switch. The base power consumed by the switch without any port is still significantly high and is not affected by EEE. Experiment results also show that the base power consumption of switches does not significantly increase with the size of the switches. Doubling the size of the switch between 24 and 48 ports increases power consumption by 35.39%. EEE has a greater effect on bigger switches, with a power (or energy) gain on the EEE-enabled 48-port switch compared to 2 x EEE-enabled 24-port switch. On the other hand, it seems to be more energy efficient to use 2 separate 24-port switches (NO EEE) than 2 separate 24-port switches (With EEE).

***Keywords*: power efficiency, EEE, switch, port, power consumption, sleep, hibernate, network traffic, burst traffic, power consumption model**

1. INTRODUCTION

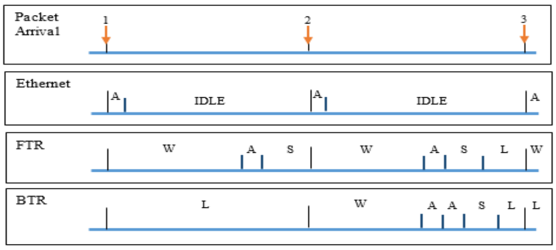
Ethernet, a technology first deployed in 1980 is the most widely used access network in the world [4]. Although in recent years, the deployment of Ethernet has decreased in homes due to wifi, it still constitutes the main technology used in core networks and cloud infrastructures, particularly in data centers. In 2010, in the US, data center power consumption is estimated at 2.3% of the total country’s power [5] while data centers worldwide are expected to grow approximately by 9% annually till 2015 [6]. Almost a quarter of the power consumption in these centers is attributed to network equipment [7] and with link speed expected to reach 200 Gbits/s [8], power consumption will undeniably, increase with time. According to our conducted experiments, the power consumption of a port increases with the increase of bandwidth. Our measurements reveal that a 1 Gbits/s port on a switch consumes 3 times more power than a 100 Mbits/s link and similarly, a fiber optic port consumes 5 times more power than a 1 Gbits/s link. This evidence the need to optimize the power consumption of network equipment which could further be enhanced by an optimal utilization rate of Ethernet links. On desktops, the average utilization of Ethernet links is at maximum 5% while that number is around 30% in data centers [9]. Consequently, for the past decade, researchers have been developing algorithms to achieve power consumption of Ethernet links that matches their utilization rates. The culmination of such research results in the standardization of EEE 802.03az in 2010 [10]. Energy-Efficient Ethernet (EEE) aims to reduce the power consumption of network equipment by running the ports in a low power mode with no imminent transmission. The ports could run in two different states: normal state where a link consumes the usual amount of power while transmitting information; and another low power mode aptly named Low Power Idle (LPI) when traffic is absent. The standard also details two transition phases namely Sleep and Wake-Up, that specifies the time it takes for the port to transition to each of the previously mentioned states. Note that the state of the ports on a network equipment is only affected by EEE. The base power consumption of a switch will not be affected by EEE, but the power consumed by a connected port is. The EEE standard also does not specify when state transitions should occur but have only provided details of which mechanism to employ bring about power saving. It is the manufacturer's onus to decide when to trigger a state change. Two mechanisms namely frame transmission (FTR) and burst transmission (BTR) are predominantly employed [11] in EEE. With FTR, the Ethernet interface is activated on the arrival of a new packet and the packet is then immediately handled. Contrastingly with BTR, the newly arrived packet is added to a queue and the interface switches to an active state once the queue is full. BTR allows packets coalescence within a certain timeout in order to avoid waking the interface excessively.

The research discussed in this paper aims to assess the benefits of deploying EEE in the core network by profiling the power consumption of an off-the-shelf Cisco 2960-X with and without power efficient protocol under different link speeds and traffic throughput.

a. Background

EEE affords implementation for different link speeds [12][29]. For example, 100 Mbits/s and 10 Gbits/s links can be powered off even if the opposite side of the link does not support EEE. It is sufficient for one side of a link to detect a lack of traffic and invoke a sleep instruction without checking what occurs on the other end of the link. However, with 1 Gbits/s links, both ends of the link must agree before invoking the sleep instruction. Furthermore, state transitions cannot be interrupted in 10 Gbits/s links. Hence, 100 Mbits/s and 10 Gbits/s links can potentially yield higher power saving at the expense of a potential delay in delivery if one end transitions to sleep mode while the other end sends traffic.

In EEE, a link can have 4 different states [10] namely Active, Low Power Idle, Sleep and Wake: **Active** (A) - a link in this state has normal operation and power consumption. This is the switch's default operational mode in the event EEE is turned off; **Sleep** (S) - is a transition state invoked when a link in state A does not detect any incoming traffic. This state lasts a finite duration denoted by T_s and its power consumption during this transition equals that of A state; **Low Power Idle** (LPI) - a link operates in low power mode which is approximately 10% of its normal power. Power savings from EEE are achieved when the link operates in LPI; **Wake** (W) - is a transition state that takes a link from LPI to A. This transition is never interrupted. This state lasts a finite duration denoted T_w and its power consumption during this transition equals that of the A state. EEE related research has predominantly focused on maximizing the LPI duration in order to maximize power savings. As previously mentioned, mechanisms used to trigger change of states in EEE are implemented by the manufacturers. The two mechanisms, frame transmission (FTR) and burst transmission (BTR) are typically employed [11] in EEE. However, the difference between them is depicted in Figure 1.



Note: FTR – Frame Transmission; BTR – Burst Transmission; A – Active; L – LowPowerIdle; S – Sleep; W – Wake;

Figure 1: An event line for Ethernet, frame transmission and burst transmission of EEE

In normal legacy Ethernet, the idle phases consume an equal amount of power compared to the active phases. However, EEE aims to minimize the power consumption of idle times with FTR and BTR. With FTR, the Ethernet interface is activated the moment a new packet arrives and the packet is then immediately handled. On the contrary, for BTR, the newly arrived packet is added to a queue and the interface switches to an active state once the queue is full. BTR affords packets coalescence within a certain timeout in order to avoid excessively waking the interface. The nature of the BTR mechanism offers a great platform for further research. Two variables play a role in BTR [14] and they are: **buffer size -** this dictates how many packets to hold in the switch before coalescing them and releasing them as a burst; **timeout -** maximum time to keep the interface in LPI mode after the first packet is added to the buffer. If the buffers fill out before timeout, all packets in the buffer are released. Similarly, if the buffer is not full and the timeout expires, the packets are also released. Tweaking these two values yields many research opportunities with researchers attempting to maximize LPI time. Increasing the buffer size without setting a timeout can lead to significant packet delay since the equipment can wait infinitely for the buffer to fill up. On the other hand, setting a timeout that is too short can lead to a decrease in potential power savings.

b. Motivation

Ethernet still constitutes the main technology deployed in core networks and cloud infrastructures (for example, in data centers). In 2010, in the US, data center power consumption is estimated to be approximately 2.3% of the total country's power [5] with data center construction worldwide estimated to grow by 9 percent each year for the next 5 upcoming years [6]. Almost a quarter of the power of these data centers is consumed by the network equipment [7] and with link speeds expected to reach 200 Gbits/s soon [8], the power consumption will undeniably increase with time. EEE aims to bring about massive power savings to core networks and data centers, thus, it is imperative to investigate the effects of this technology. Orange Telecom, the largest telecommunications service provider in France, and a collaborator in this paper is interested in assessing the economic and environmental benefits of EEE deployment on their core networks. Based on this research finding, network administrators could choose to either upgrade their core networks with the new technology or continue their business as usual.

c. Problem Definition

Standardization of EEE occurred since 2010, however, to date there is limited investigation on its benefits. Consequently, this research aims to assess the benefits of deploying EEE in the core network by modelling the power consumption of an off-the-shelf Cisco 2960-X with and without power efficient protocol under different link speeds and traffic throughput. We will first measure the power consumption of the switch without EEE under different link speeds with 1 Gbits/s being the highest available bandwidth. Subsequently, we will enable EEE and test it under different traffic throughput in order to assess the improvement it attains over legacy Ethernet. We will also compare EEE to other power saving mechanisms to better assess its benefits.

d. Delimitations

As 10Gbits/s links are still uncommon in commercial grade network equipment, no measurement could be made for this particular bandwidth. Our work revolves around profiling and modelling real equipment's power consumption but not for 10Gbits/s (and beyond) links.

This book chapter is structured as follows: Section II – Related Work; Section III – Underlying Theories; Section IV – Implementation; Section V – Results and Discussion; Section VI – Conclusion and Future Work.

2. Related work

Since 2010 (i.e. after the standardization of EEE), researchers have explored ways to maximize the energy savings. This section will review existing research on EEE energy savings profiling. Reviriego, et al. [15] conduct a research similar to our research. They create a power consumption model for small EEE enabled switches. Their results reveal that EEE switches consume similar amount of energy as legacy switches when no port is connected. They attribute this fact to hardware manufacturers not adapting their device components to EEE. Additionally, energy consumption of future switches would be very close to link utilization which is similar to work done by Paillassa, et al. [16] and Rodríguez-Pérez [17]. However, both research work utilizes simulations in ns-3 software instead of real EEE switches. Saranavan, et al. [18] assesses the benefit of EEE in High-Performance Computing scenarios. Their findings reveal that EEE reduces energy consumption of links by 70%. However, the on/off transitions of EEE greatly hamper the overall energy savings of the system. Consequently, the overall reported energy increase is merely 15% when using the default mechanisms of EEE. Saranavan and colleagues [ibid] subsequently suggest a “Power-Down Threshold” feature that keeps the link on until a certain threshold is reached. With this technique, they report savings of around 7.5% on the overall energy consumption of the system as well as a reduction in the on/off transition overhead from 25% to 2%. In 2010, Lee, et al. [13] propose a change to the MAC of optical network units in order to incorporate the interface called Slotted Delivery Mode. The Slotted Delivery method means that when traffic is low, the interface only wakes up periodically to handle the incoming and outgoing packets before going to sleep again. According to their simulations, they manage to have a power saving of 96%. Several researches explore the deployment of LPI mode. Kubo, et al. [19] propose a hybrid mechanism that combines LPI and adaptive link rate which is aimed solely at 10 Gbits/s links. This is to sleep the switch when traffic is absent and lower the link rate when link utilization is low. This hybrid mechanism manages a savings up to 84% when traffic is absent and 63% when traffic is low. These findings concur with that of Reviriego, et al. [20] and Jin, et al. [21].

Mostowfi, et al. [22] in 2015, suggest having two low-power modes in EEE in order to avoid latencies from on/off transitions. When traffic is low, EEE triggers the first stage of sleep. This stage can be woken up much faster than the default LPI. When traffic is absent after a certain threshold, a deeper sleep mode is activated. The energy consumption of this mode matches that of LPI. Therefore, this model does not save as much energy as the default model but instead improves the latencies and delays inherited from EEE implementation. Herreria-Alonso [23] extends this research by testing the two low-power modes on simulations based on real traffic scenarios. They evidence that the first stage of sleep is futile in most of their scenarios and that Deep Sleep state is preferred on the links instead of the two stage solution.

Other energy savings techniques are previously mentioned Frame Transmission (FTR) and Burst Transmission. Meng, et al. [24] in 2013, propose a new EEE policy to exploit the strength of both frame and burst transmission. The policy dictates the use of frame transmission when traffic is low, in order to avoid delay issues from burst transmission. According to Reviriego, et al. [14], using burst transmission on a 10 Gbits/s EEE link can yield up to 80% energy reduction in certain situations. Due to queueing delay from packets coalescence, these situations typically are not time sensitive (e.g. file download or file indexing on servers). However, it is worthy to note that the energy reduction is approximately 5% for video streaming and download where the packet delay can have significant impact on user quality of experience. In high traffic scenarios, Meng and colleagues' EEE policy [24] propose the use of a buffer and timeout based system. In cases where traffic is medial, the policy recommends using a buffer only system without timeout in order to receive optimum results. It is worth noting that this work has been accepted for publication in IEEE in March 2017. Mostowfi, et al. [25] reveal that setting the buffer size to 1000 packets and setting the timeout for 100 ms result in an 80% decrease in energy consumption. Their work also takes into account delay resulting from packet coalescence and estimates an average packet delay of 50 ms under normal traffic load. Their findings show that sending traffic in bursts does not add delay to packet delivery but offer lower energy savings than their advertised 80%. It is worth noting that the scenario used for their experiments is a file download scenario. Similar work is conducted by Aksić et al [26], in which they propose different buffer and time out values for different bandwidths. In 2012, Herreria-Alonso, et al. [29] develop an EEE model to explore the optimum values for buffer and timeout given an energy consumption threshold denoted by 'n'. This threshold represents the maximum allowed energy consumption percentage over the ideal minimum. The optimum configuration of variables with 'n' = 5%, results in a timeout of 120 μs and a queue of 25.73 frames. According to their simulations, burst transmission with these parameter values performs better than frame transmission in all traffic scenarios with no mention of the queueing delay created as a result. Other related work includes Chakadkit and colleagues' work [27] which involves changes in routers' control plane in routers. They present EAGER and CARE, two OSPF metrics customized for augmenting the energy saving of IEEE 802.3az line cards. Both mechanisms take into consideration traffic and congestion and adaptive link rates. They claim an energy saving that is double to that of EEE with default mechanism.

In summary, most of the related research reviewed, aims to improve benefits of EEE using burst transmission. Research focuses on developing models using network simulations and testing the models against real world traffic from internet sources. Generally, research reviewed claims savings between 50% to 90% over traditional Ethernet. However, these models are have not used real equipment in order to validate the results. Several researches explore changes to existing EEE protocol in order to maximize savings. Some integrate EEE and adaptive link rate into a single mechanism. Changing link speed is the optimum solution for low traffic times since it only slows the flow of traffic without stopping. Meanwhile, EEE can be used in downtimes where there is no imminent traffic.

Finally, our work extends the work conducted by Hossain, et al. [28] where they profile the power consumption of ethernet switches using experiments. They utilize switches similar to the ones we use for our experiments. The work concludes with a power consumption model of the switch with a multitude of variables. Our work aims to add EEE to that power consumption model in order to reflect the current status of industrial switches. Additionally, Reviriego, et al. [15] have developed a linear model for energy consumption in switches. Similarly, we shall use a linear regression to model for our measured data.

3. Underlying theories

A survey of relevant research reveals that a majority of them model energy consumption of EEE followed by validating them using network simulations. However, network simulators are not as reliable and accurate as real measurement obtained from physical network equipment. Therefore, for this research, we have obtained commercial grade network switches and evaluate their power consumption against all a set of parameters. These parameters include different bandwidths, 1Gbps, 100Mbps and 10Mbps, as well as different power savings algorithms such as EEE and sleep / hibernation.

a. Unidirectional vs Bidirectional EEE

According to the EEE standard [10], each EEE bandwidth has different implementation. For example, 10 Gbps link are unidirectional while 1 Gbps links are bidirectional in nature. A unidirectional link only needs to sense a lack of traffic on its own end before deciding to trigger an LPI mode. On the other hand, bidirectional links need to agree on both ends of the link on the lack of traffic before deciding to sleep. Imagine a scenario where two EEE capable PCs are directly connected to each other by a cable. If the link is 10Gbps, each PC decides on its own when to sleep their respective ports. On the other hand, if the link that connects the two is a 1 Gbps link, both PCs have to communicate before deciding on when to trigger sleep mode. Transitions between sleep and wake cannot be interrupted in unidirectional links. Therefore, if a packet arrives to the equipment while it is transitioning to sleep, the packet has to wait for sleep to finish and wake to be consequently triggered. Depending on the network configuration and sleep/wake transition times, this particular packet could be dropped or delayed. Bidirectionality entails longer delays in 1 Gbps links when attempting to trigger sleep mode as both sides have to agree on when to trigger it. The switches used for our research have a maximum bandwidth of 1Gbps, thus, the EEE we assess is bidirectional. This means that for our experiments, every equipment plugged into the switch is EEE capable else the interface reverts to legacy ethernet.

b. Modelling Power (and Energy) Consumption

Two types of power consumption models (with and without EEE) are abstracted from the measurements. Although different bandwidths (i.e. 10Mbps, 100Mbps, 1Gbps, or Fiber optic links) are available to test without EEE, their behavior is similar - power consumption of these ports is fixed and independent of the incoming traffic. With EEE, the power (and energy) consumption of the port is directly linked to incoming traffic. The port operates in two modes: a low power LPI mode and full higher consuming power mode. As EEE merely changes the power consumption of the equipment's ports, it is crucial for our model to accurately represent this feature. Thus, our focus is on the measurements of the power consumption of ports. The EEE model has to both reflect the impact of the technology on the ports and the total consumption.

c. Linear Regression Analysis

Linear regression is the simplest and most commonly used prediction model. This type of regression analysis is used to explain the behavior of one fixed variable against one or more independent variables. The linearity of the predicted model can help shed light on the accuracy of the model. The basic shape of a linear equation is one with only one fixed variable and another unknown, independent variable. This basic linear model can be shown by this formula: $y = c + b * x$, where y is the predicted value, c, a constant, b represents a regression coefficient, and x is the independent variable. Besides depicting correlation between different variables, regression models can also be used to forecast trends. It can provide insight into the relationship between EEE and power consumption of our switches. The power consumption of single switch ports (note: the number of switch ports is an independent variable) is the dependent variable which could be forecasted using our model. However, a primary concern with regression analysis is overfitting a model into the data by taking into account multiple independent variables. Diverse range of variables could lead to inefficient models. Simplicity of the developed model is key to its efficiency. Another concern would be under fitting a model. This problem occurs when models attempt to reveal a dependence that does not exist. This problem could arise when independent variables do not affect the independent variable. Therefore, a bias towards certain aspects of the data could falsely lead a prediction of a non-existent linearity.

4. METHODOLOGY

In this section, we describe the tools and equipment used to conduct the experiments. They include measurement tools, graphing tools and network equipment.

a. Measurement Tools


Figure 2: PowerSpy2

PowerSpy2[1] by Alciom (see Figure 2), is employed for the measurement of the switches' power consumption. Plugging the switch into PowerSpy2 yields real time data on the power consumption of the switch. PowerSpy2 is a wall plug that measures a myriad of information about the plugged devices and the device uses bluetooth to communicate the data to a special software that only runs on windows. The biggest advantage of using PowerSpy2 is its ability to detect subtle changes in power consumption. In order to measure the ports' power consumption, a measuring device that can detect variations in mW is required. PowerSpy2 has such a capability and it could measure as low as 10 mW with an accuracy of 1%. The device's baseline power consumption of 1 W is automatically deducted from its measurements in order to present the most accurate data. The Alciom software displays information on Voltage, Current and Power in real time. A multitude of logging features are available as well as providing a download facility for all measured data in a csv format. Three main functions of the Powerlog software are: automatic import of PowerSpy2 log files on real time power consumption (see Figure 3 and

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[1] http://www.alciom.com/en/products/powerspy2-en-gb-2.html

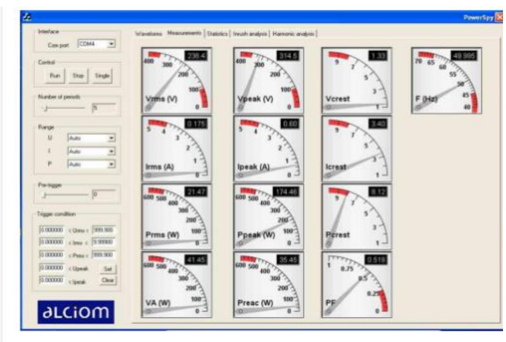


Figure 3: Real Time Power Consumption

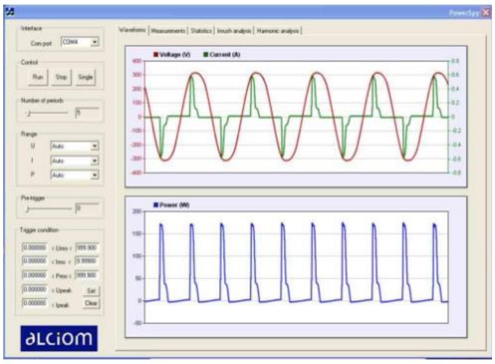
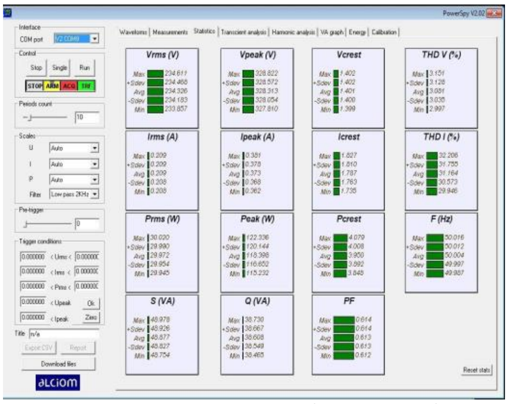


Figure 4: Power Consumption Graphing Tool



	Vrms (V)	Vpeak (V)	Vcrest	THD V (%)	Irms (A)	Ipeak (A)	Icrest	THD I (%)	Prms (W)	Peak (W)	Pcrest	F (Hz)	S (VA)	Q (VA)	PF
Max	234.611	328.822	1.402	3.151	0.209	0.381	1.827	32.206	30.020	122.336	4.079	50.016	48.978	38.730	0.614
+Sdev	234.468	328.572	1.402	3.128	0.209	0.378	1.810	31.755	29.990	120.144	4.008	50.012	48.926	38.667	0.614
Avg	234.326	328.313	1.401	3.081	0.209	0.373	1.787	31.164	29.972	118.396	3.950	50.004	48.877	38.608	0.613
-Sdev	234.183	328.054	1.400	3.035	0.208	0.368	1.763	30.573	29.954	116.652	3.892	49.997	48.827	38.549	0.613
Min	233.857	327.810	1.399	2.997	0.208	0.362	1.735	29.946	29.945	115.232	3.845	49.987	48.754	38.465	0.612

Figure 5: Statistical Calculation of Powerlog Software

the focus is on the Prms (W0 display of the dashboard), interactive power plot (see Figure 4) and statistics (see Figure 5). In Figure 4, the focus is on the power graph because it depicts the power consumption of the device. It provides a visualization of power consumption trends and could help provide insight into anomalies or problems with the equipment. The software has control facility for resetting or restarting all measurements. Figure 5 shows the following information about power consumption of the equipment: average, standard deviation, maximum and minimum values. It provides a reset facility of the statistics. The crucial part of this research is to be able to generate real traffic in order to evaluate how the network equipment reacts under real pressure. Hence, we use JPerf to generate all traffic for our experiments. JPerf is a graphic wrapper for the traffic generating utility IPerf. Details are found here[2].

Choice of Network Equipment

As our research goal is to test a piece of commercial grade equipment running EEE, we have opted for

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[2] http://wirelesslanprofessionals.com/wp-content/uploads/2011/02/How-to-Guide-on-JPerf-and-IPerf.pdf

Cisco 2960-X switch. This particular switch is advertised as an energy saving solution for small offices and businesses. Besides EEE, the switch is also equipped with sleep/hibernation techniques that allow the network administrator to configure specific times where the switches would go into hibernation mode. This mode would not allow any traffic to pass through the switches and thus significantly reduces the power consumption. The inclusion of these features in the switch allows us to pit EEE against other power saving techniques in order to better understand the benefits it yields. Experiments conducted involve the use of two 24-port and two 48-port switches. In order to capture variations that could occur in the manufacture of switches, we have opted for two different switches of the same model. We have also opted for 24-port and 48-port variations in order to investigate how power consumption of the switch scales (if any) with the size of the switch. Two different sizes of switches could demonstrate if EEE could yield better results with bigger equipment (i.e. with more number of ports).

b. Power Profiling of Switch Ports

As previously mentioned, power profiling a switch's ports is essential for the development of the power consumption model. Hence, devised experiment procedures encompass placing a switch in an idle mode without any traffic followed by connecting the switch's ports incrementally (i.e. one by one) to a network equipment. Connecting the network equipment to the switch activates that port in the switch and total power consumption for utilizing that port is monitored by PowerSpy2 and displayed by its Powerlog software. For every port that is plugged, the statistics component is reset before the experiment commences (see Figure 5) and the total power consumption of this port is logged. Each experiment is systematically carried out by connecting a port of the switch at a time until all ports of the switch have been connected. Each set of experiments involves 10 repeated runs. The architecture of our experimental setup is shown in Figure 6. As shown in Figure 6, two switches are employed for the experiments. One switch is measured by PowerSpy2 while the other serves as a hub to connect the ports. Only one switch is measured at a time in order to be able to assess the power consumption of a single port. The setup is the same for both the 24-port

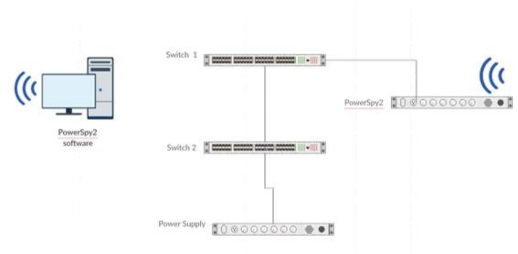

Figure 6: Architecture of the Experimental Setup for Power Profiling Switch Ports

and 48-port variants. However, the 48-port variant is matched by another 48-port variant in order to be able to connect all the ports. Our main aim of profiling the ports is to assess the impact of EEE. Hence, the set of experiments are coded into two categories namely: (with) EEE and No EEE. When EEE is not enabled, the bandwidths are switched between 10 Mbits/s, 100 Mbits/s, 1Gbits/s and Fiber optic port. However, when EEE is enabled, the only focus is on the highest available bandwidth which is 1 Gbits/s. As EEE is supposed to shut the ports when traffic is not present, coupling EEE with lower bandwidths is not a commercially viable option and consequently, only 1 Gbits/sEEE links are utilized. Experiments conducted are tabulated in Table 1. Once data is collected from these experiments, an appropriate power model is developed and utilized for the rest of the experiments.

(with) EEE	**No EEE**
1. 1 Gbits/s link speed 2. 100 Mbits/s link speed 3. 10 Mbits/s link speed 4. Fiber optic	1. 1 Gbits/s link speed

Table 1: Experiments (with) EEE and No EEE

c. Power Measurement of Switch with Different Traffic Patterns

The next set of experiments we devise are to measure the power consumption of the switch under different traffic patterns in order to better estimate the benefits of deploying EEE in core networks. As EEE is heavily influenced by traffic, we devise a set of tests to put it through its paces. We have consequently designed 4 different traffic scenarios intended to test EEE in all its different aspects. The traffic patterns are as follows:

Traffic Patterns	**Description**
Full Traffic (FT)	consists of a 100% load on the link for the entire duration of the experiment
Sinusoidal Traffic (ST)	consists of a burst traffic for 20 seconds per each minute of the experiment
Short Low Sinusoidal Traffic (LST)	consists of a burst traffic for 1 second per each minute of the experiment
Minimum Traffic (MT)	consists of a constant load of 4 kbit/s over the link for the entire duration of the experiment

Table 2: Different Traffic Patterns

In Table 2, ST and LST are examples of burst traffic chosen to test the viability of sending traffic in bursts with EEE. Such traffic patterns are preferred patterns to balance performance and savings since EEE induce power savings in LPI states. Additionally, LST is chosen based on the delay researchers claim when EEE switches between sleep and wake states. Sending a 1 second traffic forces the switch to quickly change state and hence, demonstrating the delay inherent to it. As for the MT pattern, according to the EEE standard [10], there is a threshold for incoming packet sizes that prevents EEE links from waking up. This threshold is set to prevent links from waking up under unnecessary traffic from STP packets and similar

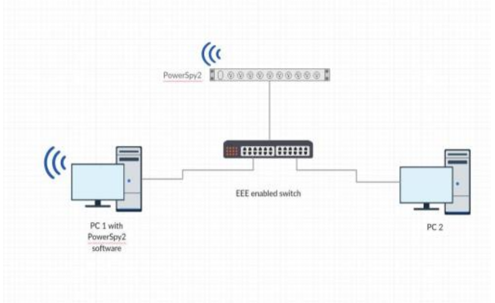

Figure 7: Architecture of the Experimental Setup for Power Measurement of Switch Based on Traffic Throughput

protocols. Therefore, if we send packets which are sufficiently small, we can theoretically send traffic without waking up the links. The MT traffic pattern is set to test this aspect of EEE while FT pattern sets the upper limit of power consumption in EEE. The architecture of the experiment setup is depicted in Figure 7. Based on Figure 7, two EEE capable PCs are connected to EEE enabled switch with PC 1 sending various traffic patterns to PC 2. The experiments run for a duration of 10 minutes. When EEE is absent, the power consumption of a port is not affected by traffic as it always operates with maximum power. Hence, no traffic pattern is used for experiments with No EEE. Experiments conducted are tabulated in Table 3.

(with) EEE	No EEE
1. FT	1. 1 Gbits/s bandwidth
2. ST	2. 100 Mbits/s bandwidth
3. LST	
4. MT	

Table 3: Experiments (with) EEE and No EEE (24-port and 48-port)

d. Compare Power Savings

The final part of the experiments is to utilize our developed model for assessing EEE against alternative solutions in a real scenario. Hence, we set up a scenario with a lab of 48 PCs. This scenario could be scaled up into a multitude of equivalent scenarios in a core network or data center environment. The options we have are either getting 2 x 24-port switches or a single 48-port switch. Each switch can either be EEE enabled or a simple legacy ethernet switch. With legacy switches, ports could be shut down manually or switches completely turned off. The first scenario would be to test the power disparity between regular legacy switches of different sizes. This scenario represents a situation where traffic is unpredictable. The network administrator does not have access to traffic information and has no prediction of Up and Down times in the network. Therefore, the PCs in the lab are left continuously running for 24 hours a day. On a legacy switch, this means that the ports will never sleep but just keep running. As the traffic is considered to be a constant 24-hour traffic, there is no way we can measure the expected energy consumption using EEE. In order to calculate the energy consumption with EEE, the number of idle hours has to be known. Additionally, two

NO EEE switches are used for this experiment. Thus, we can only use legacy switches for this scenario and this provides the opportunity to compare energy consumption of switches with differing sizes. The setup of the experiments is as follows: *two NO EEE 24-port switches versus one NO EEE 48-port switch*. Additionally, it is interesting to investigate how much to sleep the greedier option in order to come up with a better alternative. For example, how long should the two 24-port switches be shut down for their energy savings in order to match that of a single 48-port switch. This finding can inform network administrator of a better option for energy savings. On the other hand, if the network administrator knows that half of the PCs are not used at night, a second scenario could be devised in a manner whereby 24 PCs will continuously work for 24 hours a day while the remaining 24 PCs could run for 16 hours a day. Given similar switches and parameters of the first experiment, the following scenario could be arranged: *two NO EEE 24-port switches versus one EEE 48-port switch*; *two NO EEE 24-port switches versus two EEE 24-port switch.* Since a 48-port switch cannot be shut down at night as 24 ports are still needed, having a legacy 48-port switch in our scenario is not feasible. Therefore, choosing an EEE enabled 48-port switch for this scenario is a viable choice. On the other hand, as we have 24 PCs that can hibernate at night, we could then attach all these machines to the same switch and shut down the switch during the night. The second scenario arrangement is a direct comparison between EEE and legacy technologies while the first arrangement is a test of energy consumption scaling in switches. In this scenario, we can then test legacy methods of energy savings versus EEE in an attempt to see if EEE could bring about the needed benefits over its old fashioned manual counterpart.

5. RESULTS AND DISCUSSION

In this section, experimental results are presented and discussed. To reiterate experiments conducted are: with and without EEE for 24-port as well as 48-port switches; different bandwidths; and finally, different traffic patterns.

a. Power Profiling of Switch with 24 Ports (NO EEE and (with) EEE)

For each variable set (i.e. bandwidth of 1 Gbits/s, 100 Mbits/s, and 10 Mbits/s) in our methodology, all 24 ports in the switch are plugged in one by one with their corresponding power consumption measured. The base power consumption of the switch with no ports connected is measured at 30.00W. Each spike in the graphs shown in Figures 8-11, represents a new link being plugged in for an EEE enabled (and without) switch. It is noted that the increase power consumption when a link is connected is consistent. A summary of the results is tabulated in Table 4. link being plugged in for an EEE enabled (and without) switch. It is noted that the increase power consumption when a link is connected is consistent. A summary of the results is tabulated in Table 4.

Power Consumption of Switch with 24 Ports

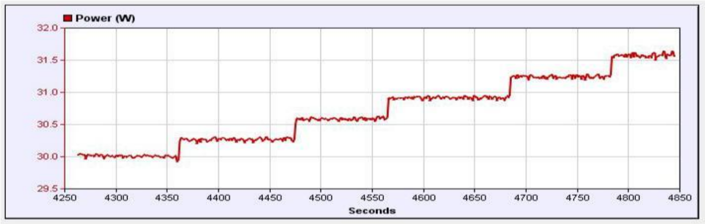

Figure 8: 1 Gbits/s link speed (no EEE)

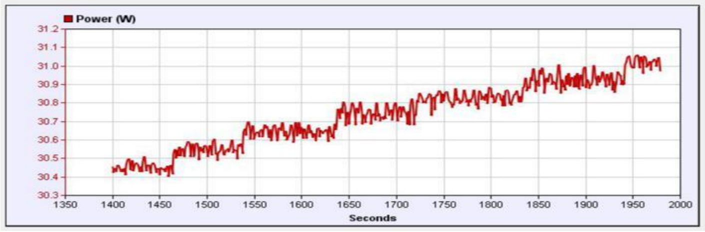

Figure 9: 100 Mbits/s link speed (no EEE)

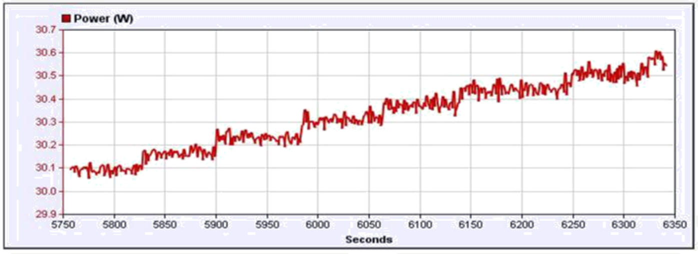

Figure 10: 10 Mbits/s link speed (no EEE)

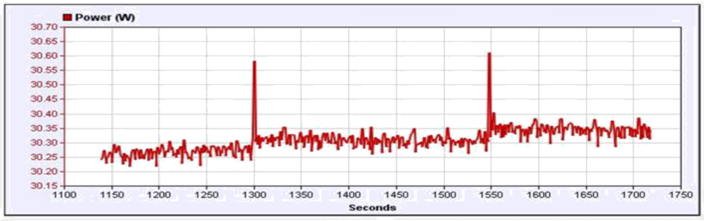

Figure 11: 1 Gbits/s link speed (with EEE)

Table 4 shows that the average power consumption of a 1 Gbits/s link (NO EEE) is approximately 3 times more than 100 and 10 Mbits/s (NO EEE) while the difference between the latter two is less pronounced. On the other hand, the average power consumption of a 1 Gbits/s link without EEE is approximately 7 times that of a 1 Gbits/s link with EEE. A graphical representation of the power consumption of the number of connected ports in a 24-port switch (NO EEE) are depicted in Figure 12. Table 4 shows that the average increase in power consumption for each connected link is approximately 0.05 W. As there is no traffic passing through the switch, this increase in power corresponds to the link in LPI mode. With the maximum power consumption of the link measured at 0.33 W for 1 Gbits/s link, LPI mode is about 15.1% of the maximum power consumption of the link.

Column A Bandwidth	**Column B Average increase in power consumption for each new link (W)**	**Column C Normalized value for Column B**	**Column D Maximum consumption for switch 24 connected ports (W)**	**Column E Normalized value for Column D**
1 Gbits/s (NO EEE)	0.33	1.00	37.88	1.00
100 Mbits/s (NO EEE)	0.10	0.16	32.28	0.16
10 Mbits/s (NO EEE)	0.07	0.07	31.66	0.07
1 Gbits/s ((with) EEE in LPI state)	0.05	0.00	31.22	0.00

Table 4: A Summary of (with) EEE and NO EEE with 24 ports

Table 5 shows that the average power consumption of a 1 Gbits/s link (NO EEE) is approximately 3 times more than 100 and 10 Mbits/s (NO EEE) while the difference between the latter two is less pronounced. On the other hand, the average power consumption of a 1 Gbits/s link without EEE is approximately 9 times that of a 1 Gbits/s link with EEE. A graphical representation of the power consumption of the number of connected ports in a 48-port switch (NO EEE) are depicted in Figure 13. Table 5 shows that the average increase in power consumption for each connected link is approximately 0.04 W. As there is no traffic passing through the switch, this increase in power corresponds to the link in LPI mode. With the maximum power consumption of the link measured at 0.35 W for 1 Gbits/s link, LPI mode is about 11.4% of the maximum power consumption of the link.

Column A Bandwidth	**Column B Average increase in power consumption for each new link (W)**	**Column C Normalized value for Column B**	**Column D Maximum consumption for switch 24 connected ports (W)**	**Column E Normalized value for Column D**
1 Gbits/s (NO EEE)	0.35	1.00	51.10	1.00
100 Mbits/s (NO EEE)	0.10	0.20	39.34	0.20
10 Mbits/s (NO EEE)	0.07	0.10	37.90	0.10
1 Gbits/s ((with) EEE in LPI state)	0.04	0.00	36.46	0.00

Table 5: A Summary of (with) EEE and NO EEE with 48 ports

b. Power Measurement of Switch According to Traffic Throughput

For this set of experiments, two EEE enabled PCs are connected to a switch, sending traffic to each other. The parameters set for these experiments (see Table 3) are: four traffic patterns (i.e. FT, ST, LST, MT); two different link bandwidths (i.e. 1 Gbits/s and 100 Mbits/s); two different technologies (i.e.

EEE and No EEE). Each experiment runs for a duration of 10 minutes. Results of the experiments have been tabulated in Tables 6 and 7. Based on the results, it is evident that for a bandwidth of 1 Gbits/s, an EEE enabled switch will be more power efficient compared with one that is without EEE. Among all the different traffic patterns (for both the 24 and 48 ports), FT is the one that is not power efficient while MT is the most power efficient.

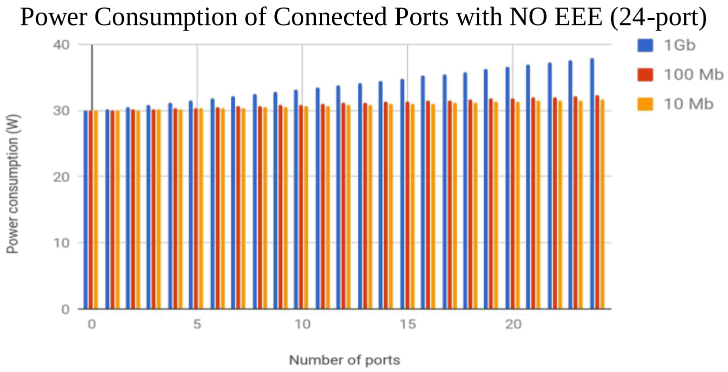

Figure 12: Power Consumption and the Number of Connected Ports with NO EEE in a 24-port Switch

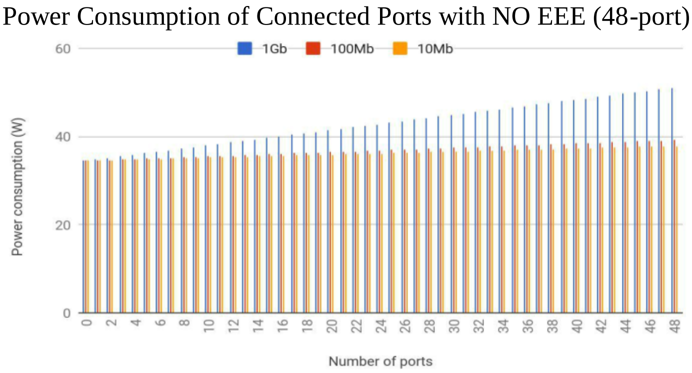

Figure 13: Power Consumption and the Number of Connected Ports with NO EEE in a 48-port Switch

Parameters (24-port)			Total Power Consumption (W)	Power Gain (%)
Bandwidth	EEE	Traffic Pattern		
1 Gbits/s	NO EEE		5.1050	0.00
100 Mbits/s	NO EEE		5.0250	1.57
1 Gbits/s	With EEE		5.0573	0.93
1 Gbits/s	With EEE	FT	5.1479	-0.84
1 Gbits/s	With EEE	ST	5.0846	0.40
1 Gbits/s	With EEE	LST	5.0613	0.86
1 Gbits/s	With EEE	MT	5.0591	0.90

Note: 1 Gbits/s (NO EEE) is used as the benchmark

Table 6: Total power consumption of a 24-port switch

Parameters (48-port)			Total Power Consumption (W)	Power Gain (%)
Bandwidth	EEE	Traffic Pattern		
1 Gbits/s	NO EEE		5.8730	0.00
100 Mbits/s	NO EEE		5.7916	1.39
1 Gbits/s	With EEE		5.7656	1.83
1 Gbits/s	With EEE	FT	5.8988	-0.44
1 Gbits/s	With EEE	ST	5.8196	0.91
1 Gbits/s	With EEE	LST	5.7755	1.66
1 Gbits/s	With EEE	MT	5.7693	1.77

Note: 1 Gbits/s (NO EEE) is used as the benchmark

Table 7: Total power consumption of a 48-port switch

c. Overview of Power Consumption of EEE-enabled Switches

The base power consumption of a 24-port switch with EEE (i.e. 30.10 W) is slightly higher than the switch without EEE (30.00 W see Section V.A). Once our PCs are connected, this power consumption rises to 30.19 W (see Figure 18). Our previous experiments show that a port in LPI consumes around 0.05 W power. The increase in power consumption approximately corresponds to the sum of two LPI consumption (hence, this data confirms previous LPI measurements). Once traffic reaches the switch, it seems that the power consumption corresponds accordingly and rises to 30.72 W (see Figure 18). This rise can be attributed to the ports moving to an LPI to an active state. This increase in power consumption is measured at around 0.25 W per port. The sum of this figure and LPI consumption is 0.30 W, which approximately corresponds to the power consumption of 1 Gbits/s link with NO EEE (see Table 4). Therefore, with no traffic, the EEE link consumes around 2.02% of its possible maximum power value and the link consumes the maximum power value once a traffic arrives. It seems there is no visible real time delay between the sleep and wake transitions. The base power consumption of a 48-port switch with EEE is at 34.54 W (see Section V. B).

Once our PCs are connected, this power consumption rises to 34.62 W. Our previous experiments show that a port in LPI consumes around 0.04 W (see Table 5). The increase in power consumption approximately corresponds to the sum of two LPI consumption (once again, this data confirms our previous measurements of LPI).

When traffic reaches the switch, it seems that power consumption corresponds accordingly and rises to 35.21 W (see Figure 19). This rise could be attributed to the ports moving from an LPI to an active state. This increase in power consumption is measured at around 0.30 W per port. If we add the LPI consumption to this figure, the result is 0.34 W, which corresponds to the power consumption of 1 Gbits/s link with No EEE (see Table 5). Therefore, with no traffic, the EEE link consumes approximately 1.90% of its maximum power value and the link consumes the maximum power value on the arrival of the traffic. To reiterate, there is no visible real time delay between the sleep and wake transitions.

Power Consumption of Switch with 48 Ports

Figure 14: 1 Gbits/s link speed (no EEE)

Figure 15: 100 Mbits/s link speed (no EEE)

Figure 16: 10 Mbits/s link speed (no EEE)

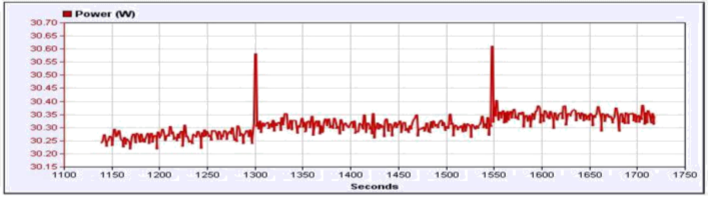

Figure 17: 1 Gbits/s link speed (with EEE)

Power Consumption of EEE enabled Switch with ST Traffic Pattern

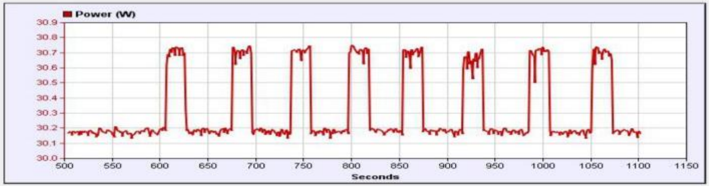

Figure 18: 24-port

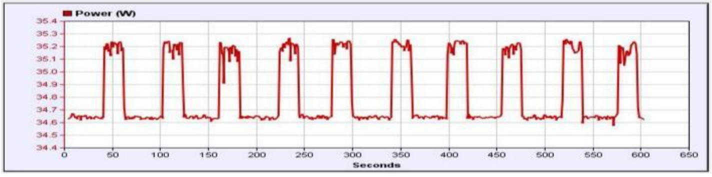

Figure 19: 48-port

d. Comparison of Power Consumption of 24-port and 48-port Switches (With and Without EEE)

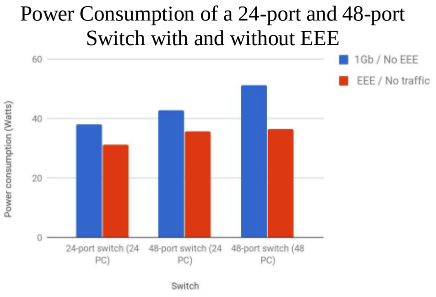

Figure 20: 24-port and 48-port Switches

To reiterate, the base power consumption of the 24-port and 48-port switches without any ports connected is 30.00 W and 34.54 W respectively. The power consumption of the switches after connecting the ports, are shown in Figure 20. Without EEE, the difference in the power consumption is quite significant with the 48-port consuming 51.1 W compared to 37.88 W for the 24-port. The difference is less stark with EEE-enabled where the consumption of the switch is 31.30 W and 35.61 W for the 24-port and 48-port variants respectively. It is also noted that the power consumption of a single switch port is slightly higher on the 48-port variant measuring at 0.35 W compared to its 24-port counterpart measuring at 0.33 W. Another point to note is that when connecting 24 PCs to the 48-port switch, the difference between the power consumption of the switch and that of a 24-port one is merely the difference between their base power. As the links for both switches consume almost the same amount of power, the only difference between the two is the increased number of ports on the 48-port switch and the slight increase in base power consumption when no port is connected. These results are tabulated Tables 8 and further comparative analysis has been tabulated in Table 9. As the 48-port switch with all the ports connected has the highest total power consumption, it is used as the benchmark for the other configurations. The power gain indicates the power efficiency of using EEE-enabled switches. Based on the analysis shown in Table 8, a 48-port with 48 connected pcs seem to indicate the highest power gain. Table 9 depicts calculated power ratios to facilitate easy comparison. Based on the tabulated results, the following conclusions could be drawn. Firstly, a 24-port EEE-enabled switch with 24 connected pcs is more power efficient than a 48-port EEE-enabled switch with 24 connected pcs. On the other hand, a 48-port EEE-enabled switch with 48 connected pcs is more power efficient that two 24-port EEE-enabled switch with 48 connected pcs.

Parameters				**Power Consumption (W)**		**Power Gain (%)**
Switch	**No. of Connected PCs**	**Bandwidth**	**Traffic**	**NO EEE**	**WITH EEE**	
24-port	24	1 Gbits/s	No Traffic	37.88	31.30	17.37
48-port	24	1 Gbits/s	No Traffic	42.82	35.52	17.05
48-port	48	1 Gbits/s	No Traffic	51.10	36.51	28.55

Note: Power Gain is calculated efficiency gained for switches WITH EEE compared to NO EEE

Table 8: Power Consumption for different configurations (With and Without EEE)

Parameters				Power Consumption			
Switch	No. of Connected PCs	Bandwidth	Traffic	NO EEE (W)	Power Ratio (NO EEE)	WITH EEE (W)	Power Ratio (WITH EEE)
24-port	24	1 Gbits/s	No Traffic	37.88	1.21	31.30*	1.00
48-port	24	1 Gbits/s	No Traffic	42.82	1.37	35.52	1.13
48-port	48	1 Gbits/s	No Traffic	51.10	1.63	36.51	1.17
2 x24-port	48	1 Gbits/s	No Traffic	75.76	2.42	62.60	2.00

Note: The reference value is the lowest power consumption value with *. Additionally, the values for 2 x 24-port are derived from one 24-port for comparison purposes

Table 9: Power Ratio for different configurations (With and Without EEE)

e. Estimated Power (and Energy) Consumption Models

The development of the power and energy models (see Table 10) for the switches in this research are derived from measurements discussed in preceding sections in this book chapter. As previously mentioned, a traffic of 4 kbps (see Table 2) or less does not trigger a port to wake up. Hence, the power (and energy) consumption equation has to consider this condition. Consequently, when traffic is 4kbps or less, all ports remain in LPI mode.

Switch	Model	Key		
NO EEE	$P_S = (N_P \times P_P) + P_B$ (1)		P_S	Power consumption of switch (W)
			P_P	Power consumption of a single port (W)
			P_B	Base power consumption of switch with no connected port (W)
With EEE	$P_S = (N_{SP} \times P_{LPI}) + (N_{AP} \times P_{LPI}) + P_B$ (2)		P_{LPI}	Power consumption of a single port in LPI state (W)
			N_P	Number of connected ports
			N_{SP}	Number of ports in sleep state (ports with no traffic running through them)
			N_{AP}	Number of active ports (ports with traffic running through them)
With EEE	For B > 4kbps $E_S = P_B \times T_D + N_{AP} \times (P_P \times T_A) + N_{SP} \times (P_{LPI} \times T_S)$ (3)		E_S	Energy consumption of switch (Wh)
			B	Bandwidth (kbps)
	For B <= 4kbps $E_S = (P_B + N_P \times P_{LPI}) \times T_D$ (4)		T_A	Total duration with traffic (h)
			T_S	Total duration without traffic (h)
			T_D	Total duration of experiment (h) $T_D = T_A + T_S$

Table 10: Power (and Energy) Consumption Models for the Switches

f. Deployment of the Power (and Energy) Models to Estimate Power (and Energy Savings)

In this section of the chapter, we shall use two scenarios to demonstrate how the Power (and Energy) Consumption Models tabulated in Table 10 are deployed (see Tables 11 - 13).

Scenario (1 Gbits/s)	Formula Substitution	Measured Values
Scenario 1.1 One NO EEE 24-port switch	**Use Equation 1 (Table 11)** $P_{24} = (24 \times P_P) + P_B$ $= 24 \times 0.33 + 30.00$ W $= 37.92$ W	**Per Port** $P_P = 0.33$ W (for 24-port, from Table 4) $P_P = 0.35$ W (for 48-port, from Table 5)

Scenario 1.2 Two NO EEE 24-port switches	$P_{24\,x\,2}$ = 2 x P_{24} = 2 x 37.92 W = 75.84 W $E_{24\,x\,2}$ = 75.84 W x 24 h = 1820.26 Wh (per day)	**Per Switch** P_B = 30.00 W (for 24-port from Section V. A) P_B = 34.54 W (for 48-port from Section V. B)
Scenario 1.3 One NO EEE 48-port switch	**Use Equation 1 (Table 11)** P_{48} = (48 x P_P) + P_B = 48 x 0.35 + 34.54 W = 51.34 W E_{48} = 51.34 W x 24 (h) (per day) = 1232.16 Wh	N_P = 24 (for 24-port switch) N_P = 48 (for 48-port switch) T_D = 24h (per day)
Conclusion 1 Drawn for Scenarios 1.1-1.3	P_{48} > P_{24}, and the increase in power consumption is 35.39%. E_{48} < $E_{24\,x\,2}$, therefore, it is more energy efficient to use one 48-port switch then 2 separate 24-port switches and the energy gain is 32.30%.	
Scenario 1.4 Analysis for NO EEE 24-port and 48-port switches	**Assumption:** There are two 24-port and one 48-port switches. Based on conclusion 1, the energy consumption (per day) for a 48-port is less than two 48-ports. The goal of the following analysis is to investigate how many hours to sleep the 2 x 48-port switches (per day) in order to bring about energy savings compared to 1 x 48-port switch. 2 x P_{24} x T_A <= E_{48} (from Scenario 1.3) 2 x P_{24} x (24 - T_S) <= E_{48} T_S => 24 – [E_{48}/(2 x P_{24}) (substitute for E_{48} and P_{24}) with values from Scenarios 1.1 and 1.3) T_S => 7.753 hours per day	T_A = Duration for an active port T_S = Duration for a sleeping port
Conclusion 2 Drawn for Scenario 1.4	The 2 x 24-port switches will have to sleep for at least 7.753 hours per day in order to be more energy efficient than 1 x 48-port switches (with NO EEE)	

Table 11: Scenario 1 - Deployment of Power (and Energy) Consumption Models for the Switches (NO EEE)

Scenario (1 Gbits/s)	Formula Substitution	Measured Values
Scenario 2.1 Two NO EEE 24-port switches	**Scenario 2.1.1 Assumption** One 24-port runs for 24h while another runs for 16h per day. From Scenario 1.1, the power consumption of a NO EEE 24-port switch is: P_{24} = 37.92 W T_{D1} = 24h and T_{D2} = 16h E_{24x2} = (24 x P_{24}) + (16 x P_{24}) = (24 x 37.92) + (16 x 37.92) Wh = 1516.80 Wh	Per Port P_P = 0.33 W (for 24-port, from Table 4) P_P = 0.35 W (for 48-port, from Table 5) P_{LPI} = 0.05 W (for 24-port, from Section V. A) P_{LPI} = 0.04 W (for 48-port, from Section V. B)
	Scenario 2.1.2 Assumption Both 24-port switches run for 16h per day. From Scenario 1.1, the power consumption of a NO EEE 24-port switch is: P_{24} = 37.92 W T_{D2} = 16h E_{24x2} = 2 x (16 x P_{24}) = 1213.44 Wh	Per Switch P_B = 30.00 W (for 24-port from Section V. A) P_B = 34.54 W (for 48-port from Section V. B)
Scenario 2.2 One EEE 48-port switch	**Assumption** All 48 ports run continuously for 16h (per day) Only 24 ports (out of the 48 ports) run continuously for the remaining 8 hours while the other 24 ports are in sleeping mode	N_P = 24 (for 24-port switch) N_P = 48 (for 48-port switch) N_{AP1} = 48 N_{AP2} = 24 N_{SP1} = 0 N_{SP2} = 24

	Part 1 Use Equation 3 (see Table 11) and $T_{D2} = 16h$ $E_{48(D2)} = P_B \times T_{D2} + N_{AP1} \times (P_P \times T_{A1}) + N_{SP1} \times (P_{LPI} \times T_{S1})$ $E_{48(D2)} = 34.54 \times 16 + 48 \times (0.35 \times 16) + 0 \times (0.04 \times 0)$ $E_{48(D2)} = 821.44$ Wh **Part 2** Use Equation 3 (see Table 11) and $T_{D3} = 8h$ $E_{48(D3)} = P_B \times T_{D3} + N_{AP2} \times (P_P \times T_{A2}) + N_{SP2} \times (P_{LPI} \times T_{S2})$ $E_{48(D3)} = 34.54 \times 8 + 24 \times (0.35 \times 8) + 24 \times (0.04 \times 8)$ $E_{48(D3)} = 351.20$ Wh **Part 3** The total energy consumption per day $E_{48(Total)} = E_{48(D2)} + E_{48(D3)}$ $E_{48(Total)} = 821.44 W + 351.20 W = 1172.64 W$	$T_{D1} = 24h$ (per day) $T_{D2} = 16h$ (per day) $T_{D3} = 8h$ (per day) $T_{A1} = 16h$ (per day) $T_{A2} = 8h$ (per day) $T_{S1} = 0h$ (per day) $T_{S2} = 8h$ (per day) B > 4kbps
Conclusion 3 Drawn for Scenarios 2.1.1-2.2	Based on Scenario 2.1.1, $E_{48} < E_{24 \times 2}$, therefore, it is more energy efficient to use one 48-port switch than 2 separate 24-port switches so that some of the ports can go to sleep when there is reduced traffic. The energy gain for Scenario 2 is 22.68%. Based on Scenario 2.1.2, $E_{48} < E_{24 \times 2}$, therefore, it is more energy efficient to use one 48-port switch than 2 separate 24-port switches for the same running condition of 16h per day. The energy gain for Scenario 2 is 2.69%.	

Table 12: Scenario 2 - Deployment of Power (and Energy) Consumption Models for the Switches (EEE and NO EEE)

Scenario (1 Gbits/s)	Formula Substitution	Measured Values
Scenario 3.1 Two NO EEE 24-port switches	**Assumption** One 24-port switch runs for 24h (per day) while the other runs for 16h (per day). $T_{D1} = 24h$ and $T_{D2} = 16h$ Use the outcome of Scenario 1.1 $E_{24x2} = 1516.80$ Wh	Per Port $P_P = 0.33$ W (for 24-port, from Table 4) $P_P = 0.35$ W (for 48-port, from Table 5) $P_{LPI} = 0.05$ W (for 24-port, from Section V. A) $P_{LPI} = 0.04$ W (for 48-port, from Section V. B) Per Switch $P_B = 30.00$ W (for 24-port from Section V. A) $P_B = 34.54$ W (for 48-port from Section V. B)
Scenario 3.2 Two EEE 24-port switches	One 24-port switch runs for 24h (per day) while the other 24-port switch runs for 16h only (per day) with 8h in sleep mode. $T_{D1} = 24h$ and $T_{D2} = 16h$ **Part 1** Use Equation 3 (see Table 11) and $T_{D1} = 24h$ (all 24 ports are active) $E_{24(D1)} = P_B \times T_{D1} + N_{AP1} \times (P_P \times T_{A1}) + N_{SP1} \times (P_{LPI} \times T_{S1})$ $E_{24(D1)} = 30.00 \times 24 + 24 \times (0.33 \times 24) + 0 \times (0.05 \times 0)$ $E_{24(D1)} = 910.08$ Wh **Part 2** Use Equation 3 (see Table 11) and $T_{D2} = 16h$ (all 24 ports are active) $E_{24(D2)} = P_B \times T_{D2} + N_{AP2} \times (P_P \times T_{A2}) + N_{SP2} \times (P_{LPI} \times T_{S2})$ $E_{24(D2)} = 30.00 \times 16 + 24 \times (0.33 \times 16) + 0 \times (0.05 \times 0)$ $E_{24(D2)} = 606.72$ Wh **Part 3** Use Equation 4 (see Table 11) and $T_{D3} = 8h$ (all 24 ports are sleeping) $E_{24(D3)} = (P_B + N_P \times P_{LPI}) \times T_{D3} = (30.0 + 24 \times 0.05) \times 8$ Wh $= 249.60$ Wh	$N_P = 24$ (for 24-port switch) $N_P = 48$ (for 48-port switch) $N_{AP1} = 24$ $N_{AP2} = 24$ $N_{SP1} = 0$ $N_{SP2} = 0$ $N_{SP2} = 24$ $T_{D1} = 24h$ (per day) $T_{D2} = 16h$ (per day) $T_{D3} = 8h$ (per day) $T_{A1} = 24h$ (per day) $T_{A2} = 16h$ (per day) $T_{A3} = 0h$ (per day) $T_{S1} = 0h$ (per day) $T_{S2} = 0h$ (per day) $T_{S3} = 8h$ (per day) B > 4kbps (for Part 2) B <= 4kbps (for Part 3)

	The total energy consumption per day $E_{24x2(Total)} = E_{24(D1)} + E_{24(D2)} + E_{24(D3)}$ $E_{24(Total)} = 910.08Wh + 606.72\ Wh + 249.60\ Wh = 1776.40\ W$	
Conclusion 4 Drawn for Scenarios 3.1-3.2	$E_{24\ x\ 2}$ (With EEE) < $E_{24\ x\ 2}$ (NO EEE) , therefore, it is more energy efficient to use two 24-port switches (NO EEE) than 2 separate 24-port switches (With EEE) though one 24-port switch go to sleep for 8h. The energy loss for Scenario 3 is 16.46%	

Table 13: Scenario 3 - Deployment of Power (and Energy) Consumption Models for the Switches (EEE and NO EEE)

In summary, results from power profiling the switch's ports firstly showcase that without EEE, the power consumption of 1 Gbits/s link on a 24-port switch is on average 0.33 W for each new link added. Results from power profiling the ports on the 48-port switch on the other hand, firstly showcase, that without EEE, the consumption of 1 Gbits/s link is on average 0.35 W for each new link added. A 1 Gbits/s link then consumes 3 times more than a 100 Mbits/s with the latter consuming slightly more than 10 Mbits/s. The total energy consumption for a NO EEE 48-port is less that two separate NO EEE 24-port switches. If both run continuously for 24h per day, the energy gain is 32.30%. Several scenarios have been created for the deployment of EEE-enabled 24-port and 48-port switches. One of the results to be highlighted for a scenario in Table 13 (2xNO EEE 24-port switch – one run for 24h while the other 16h per day; and 2 x EEE 24-port switch – same running conditions) is that the latter incurs an energy loss of 16.46% when compared with the former.

6. CONCLUSION

During our experimentation, we have explored the power (and energy) consumption of links in relation to their bandwidths and conclude that the power (and energy) consumption of ports will exponentially increase with the increase of speed. With the emerging 10 Gbits/s links, the expected power (and energy) efficiency of those links will surpass our measured values for 1 Gbits/s links. Our experimental measurements reveal that an EEE port runs at 12-15% of its total power when in low power mode. Therefore, the power savings (when no traffic is present) can constantly exceed 80%. However, our measurements equally show that the power (energy) consumption of a single port represents less than 1% of the total power (energy) consumption of the switch. The base power consumed by the switch without any port is still significantly high and is not affected by EEE. Experiment results also show that the base power consumption of switches does not significantly increase with the size of the switches. When doubling the size of the switch between 24 and 48 ports, we measure an increase of 35.39% in power (or energy) consumption. EEE also holds greater effect on bigger switches, with the power (or energy) gain on the EEE-enabled 48-port switch compared to

2 x EEE-enabled 24-port switch. However, it seems to be more energy efficient to use 2 separate 24-port switches (NO EEE) than 2 separate 24-port switches (With EEE).

The best use case for EEE is hence one where the equipment is very large and the traffic has a lot of downtime. According to statistics from Technavio [6], big data centers with link utilization rates of 30% and where the equipment is very large, presents a perfect customer for a mass adoption of EEE. However, office spaces and computer labs will not sufficiently receive energy savings to justify a mass adoption of the technology. The implementation of EEE on the other hand, has delivered protocol related performance. There is no noticeable delay in transitioning from Sleep to Wake and the protocol delivers small but noticeable energy savings over regular 1 Gbps. Consequently, significant interest in re-implementing these tests on link speeds of 10Gbps and higher in order to assess potential benefits from EEE for such bandwidths. For future work, similar tests should be conducted for larger switches in order to test the benefits of deploying EEE in large data centers. Similarly, conducting similar tests on switches with different models and manufacturers will help generalize the results presented in this work.

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References

[1] El Khoury, J. (2017). Assessing the benefit of deploying EEE on commercial grade network switches, Unpublished PERCCOM Masters Dissertation, University of Lorraine, Nancy, France.

[2] Kharchenko, V., Kondratenko,Y., Kacprzyk, J. (Eds). Green IT Engineering: Concepts, Models, Complex Systems Architectures. Studies in Systems, Decision and Control, Vol. 74. Springer, Cham (2017), DOI: 10.1007/978-3-319-44162-7.

[3] Kharchenko, V., Kondratenko, Y., Kacprzyk, J. (Eds). Green IT Engineering: Components, Networks and Systems Implementation. Studies in Systems, Decision and Control, Vol. 105. Springer, Cham (2017), DOI: 10.1007/978-3-319-55595-9.

[4] Meng, J, Ren, F, Jiang, W, et al. (2013). Modeling and Understanding Burst Transmission Algorithms for Energy Efficient Ethernet, IEEE/ACM 21st International Symposium on IEEE on Quality of Service (IWQoS), 3-4 June 2013, 2013, Montreal, QC, Canada, DOI: 10.1109/IWQoS.2013.6550278.

[5] Brill, K. G. (2007). The Invisible Crisis in the Data Center: The Economic Meltdown of Moore's Law, White Paper, Uptime Institute, url: http://www.mm4m.net/library/The_Invisible_Crisis_in_the_Data_Center.pdf , accessed date: [27/10/2017].

[6] Technavio. (2017). Global Data Center Construction Market 2017-2021, url: https://www.technavio.com/report/global-data-center-global-data-center-construction-mark et-2017-2021, accessed date: [27/10/2017].

[7] Armbsrust, M., et al. (2009). Above the Clouds: A Berkeley View of Cloud Computing, Technical Report UCB/EECS-2009-28, EECS Department, U.C. Berkeley, Feb. 2009, url: http://cacs.usc.edu/education/cs653/Armbrust-CloudComp-Berkeley09.pdf, accessed date: [27/10/2017].

[8] Seoane, I., Hernandez, J. A., Reviriego, P., and Larrabeiti, D. (2011). Energy-aware flow allocation algorithm for Energy Efficient Ethernet networks, Proceedings of 19th International Conference on Software, Telecommunications and Computer Networks, SoftCOM, 15-17 Sept. 2011, Split, Yugoslavia.

[9] Gunaratne, C., Christensen, K., Nordman, B., and Suen, S. (2008). Reducing the Energy Consumption of Ethernet with Adaptive Link Rate (ALR), IEEE Transactions on Computers, Vol. 57, Issue 4, April 2008, pp. 448-461, DOI: 10.1109/TC.2007.70836.

[10] IEEE. (2010). IEEE P802.3az Energy Efficient Ethernet Task Force, url: http://www.ieee802.org/3/az/, accessed date: [27/10/2017].

[11] Christensen, K., et al. (2010). IEEE 802.3az: The Road to Energy Efficient Ethernet, IEEE Communications Magazine, Vol. 48, Issue 11, pp. 50-56, Nov. 2010, DOI: 10.1109/MCOM.2010.5621967

[12] Marsan, M. A., et al. (2011). A Simple Analytical Model for Energy Efficient Ethernet, IEEE Communications Letters, Vol. 15, Issue 7, pp.773-775, July 2011, DOI: 10.1109/LCOMM.2011.060111.110973.

[13] Lee., S., and Chen, A. (2010). Design and analysis of a novel energy efficient ethernet passive optical network, Proceedings of the 9th International Conference on Networks (ICN), 11-16 April, 2010, Menuires, France, DOI: 10.1109/ICN.2010.9.

[14] Reviriego, P., et al. (2010). Burst Transmission for Energy-Efficient Ethernet, IEEE Internet Computing, Vol.14, Issue 4, pp. 50-57, July/August, 2010, DOI: 10.1109/MIC.2010.52.

[15] Reviriego, Pedro, et al. (2012). An energy consumption model for energy efficient ethernet switches, Proceedings of IEEE International Conference on High Performance Computing and Simulation (HPCS), 2-6 July, 2012, Madrid, Spain, DOI: 0.1109/HPCSim.2012.6266897.

[16] Paillassa, B., et al. (2013). Performance evaluation of energy efficient policies for ethernet switches, Proceedings of IEEE International Wireless Communications and Mobile Computing Conference (IWCMC), 1-5 July, 2013, Sardinia, Italy, DOI: 10.1109/IWCMC.2013.6583659

[17] Popescu, I, et al. (2015). Application-centric energy-efficient Ethernet with quality of service support, Electronics Letters, Vol. 51(15), pp.1165-1167, DOI: 10.1049/el.2015.0999.

[18] Saravanan, K. P., Carpenter, P. M., and Ramirez, A. (2013). Power/performance evaluation of energy efficient Ethernet (EEE) for high performance computing, IEEE International Symposium on Performance Analysis of Systems and Software (ISPASS), 21-23 April 2013, Austin, Texas, USA, DOI: 10.1109/ISPASS.2013.6557171

[19] Kubo, Ryogo, et al. (2010). Study and demonstration of sleep and adaptive link rate control mechanisms for energy efficient 10G-EPON. Journal of Optical Communications and Networking, Volume 2, Issue.9, pp.716-729, DOI: 10.1364/JOCN.2.000716.

[20] Reviriego, Pedro, et al. (2012). Study of the potential energy savings in ethernet by combining energy efficient ethernet and adaptive link rate. Transactions on Emerging Telecommunications Technologies 23.3, pp. 227-233, doi: https://doi.org/10.1002/ett.1526.

[21] Jin, Shunfu, Rongyu Fan, and Wuyi Yue. (2012). A hybrid energy saving strategy with LPI and ALR for energy-efficient ethernet. Proceedings of IEEE 2nd International Conference on Computer Science and Network Technology, (ICCSNT), 29-31 Dec. 2012, Changchun, China, DOI: 10.1109/ICCSNT.2012.6525945.

[22] Rodríguez-Pérez, Miguel, et al. (2015). Optimum Traffic Allocation in Bundled Energy-Efficient Ethernet Links. IEEE Systems Journal, Issue 99, DOI: 10.1109/JSYST.2015.2466086.

[23] Herreria-Alonso, Sergio, et al. (2017). Optimizing Dual-Mode EEE Interfaces: Deep-Sleep Is Healthy. IEEE Transactions on Communications, Vol. 65(8), DOI: 10.1109/TCOMM.2017.2700310.

[24] Larrabeiti, D., et al. (2011). Towards an energy efficient 10 Gb/s optical ethernet: Performance analysis and viability, Optical Switching and Networking, Vol. 8, Issue 3, 2011, pp.131-138, doi:10.1016/j.osn.2011.03.009.

[25] Mostowfi, M., and K. Christensen, K. (2011). Saving Energy in LAN Switches: New Methods of Packet Coalescing for Energy Efficient Ethernet, Proceedings of IEEE IGCC Orlando, USA, 25-28 July 2011, DOI: 10.1109/IGCC.2011.6008547.

[26] Aksić, M., and M. Bjelica. (2014). Packet coalescing strategies for energy-efficient Ethernet. Electronics Letters, Volume 50, Issue 7, pp.521-523, DOI: 10.1049/el.2014.0386.

[27] Chakadkit,T., Jakllari, G., and Paillassa, B. (2015). Augmenting the energy-saving impact of IEEE 802.3 az via the control plane. Proceedings of IEEE International Conference on Communication Workshop, (ICCW), 8-12 June 2015, London, UK, DOI: 10.1109/ICCW.2015.7247610.

[28] M. Hossain, E. Rondeau, J.-P. Georges, T. Bastogne, Modeling the power consumption of Ethernet Switch, International SEEDS Conference 2015: Sustainable Ecological Engineering Design for Society, 17-18 September 2015, Leeds, UK.

[29] Herreria-Alonso, S., Rodrıguez-Perez, Fernandez-Veiga, M., and Lopez-Garcıa, C. (2012). Optimal Configuration of Energy-Efficient Ethernet, Elsevier Computer Networks, Volume 56, Issue 10, pp. 2456-2467, July,2012, doi: https://doi.org/10.1016/j.comnet.2012.03.006.

[30] Klimova, A., Rondeau, E., Andersson, K., Porras, J., Rybin, A.V., and Zaslavsky, A. (2016). An international Master's program in green ICT as a contribution to sustainable development. Journal of Cleaner Production, Vol. 135, 1 November, 2016, pp. 223-239, doi: https://doi.org/10.1016/j.jclepro.2016.06.032.