An Energy Consumption Model for Energy Efficient Ethernet Switches

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Abstract— **Ethernet is one of the first computer networking technologies for which a standard has been developed to improve its energy efficiency. The Energy Efficient Ethernet (IEEE 802.3az) standard was approved in 2010 and is expected to enable savings of several Terawatt hours (TWh) per year. As switches that implement the standard become available and are deployed, it is important to understand how their energy consumption depends on the number of active ports and their traffic. In this paper the energy consumption of small Energy Efficient Ethernet switches is analyzed in several experiments and based on the results a model for the energy consumption of Energy Efficient Ethernet switches is proposed. The model can be used to predict the energy savings when deploying the new switches and also for research on further energy saving techniques such as energy efficient routing or dynamic link shutdown.**

Index Terms— **IEEE 802.3, Energy Efficient Ethernet, power management, energy-aware systems, local area networks.**

I. INTRODUCTION

ENERGY efficiency is becoming an important issue in computing and networking. This is due to both environmental concerns and economic costs associated with energy consumption. The overall consumption of computing equipment is predicted to grow substantially in this decade unless energy efficiency mechanisms are incorporated in computing systems [1]. The issue affects both high performance computing facilities such as datacenters and end user equipment. For example, the energy consumed by a data center is a key operational cost [2] and the aggregated consumption of end user devices is significant due to the large number of devices [3]. It has been observed that the energy consumption is in many cases almost constant and independent of the system load [4]. This results in poor energy efficiency for lightly loaded systems. Therefore energy efficiency of computing and networking systems can be significantly improved by making the energy consumption more proportional to system load.

The energy consumption of networking equipment is relevant and only for the Internet was estimated to be over 6 Twh in 2000 [5]. More recent studies suggest a larger consumption when end user equipments and access networks are considered [6]. Although their individual power consumption is small, most of the energy is consumed by devices in the access network and end user premises. This is explained by the large number of such devices compared to core or transport network devices.

One of the first networking technologies for which energy efficient mechanisms have been defined in a standard is Ethernet. The Energy Efficient Ethernet IEEE 802.3az standard approved in September 2010, defines a low power mode that improves the energy efficiency of Ethernet physical layer devices [7]. With an installed base of over one billion devices, the expected energy savings have been estimated in over 4 Twh [8]. Products that implement the standard are becoming common in the market and wide adoption is expected to occur in a few years. The use of Energy Efficient Ethernet (EEE) will change the energy consumption profile of switches making it more proportional to the traffic load [9]. However current products that implement EEE do not provide much information on the energy consumption profile [10],[11],[12],[13]. Typically only minimum and maximum power consumption levels are given. In this paper an in-depth analysis of the power consumption profile of small Ethernet switches is presented. Based on the results a model for the energy consumption of EEE enabled Ethernet switches is proposed. The model can be used by researchers that want to explore higher layer energy saving mechanisms like energy efficient routing [14] or selective link deactivation [15]. This would allow them to make realistic estimates of the savings that would be achieved by those techniques in Ethernet networks.

The rest of the paper is organized as follows, in section II an overview of Energy Efficient Ethernet is provided followed by a review of the current power consumption of small Ethernet switches in section III. In section IV the power consumption of two small Energy Efficient Ethernet switches is evaluated in a set of experiments. Based on the results a simple model for the energy consumption of Energy Efficient Ethernet switches is presented in section V. Finally section VI discusses the implications of the results and the conclusions are presented in section VII.

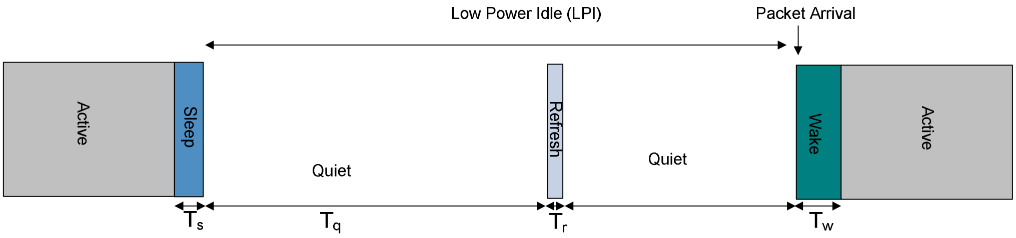

Figure 1. Mode transitions in Energy Efficient Ethernet

Table I. Minimum wake, sleep, frame transmission times and single frame efficiencies for different link speeds

Protocol	Min T_w (µsec)	Min T_s (µsec)	Frame size (bytes)	T_{Frame} (µsec)	Single Frame efficiency	Frame size (bytes)	T_{Frame} (µsec)	Single Frame efficiency
100BASE-TX	30.5	200	1518	120	34.2%	64	5.1	2.2%
1000BASE-T	16.5	182	1518	12	5.7%	64	0.5	0.3%
10GBASE-T	4.48	2.88	1518	1.2	14.0%	64	0.05	0.7%

II. OVERVIEW OF ENERGY EFFICIENT ETHERNET

For many years, Ethernet has been the dominant technology for wire-line LANs. It is widely used in residences and commercial buildings and almost all computers include an Ethernet connection and in some cases more than one. Although Ethernet supports a variety of transmission media, most of the Ethernet ports are connected by Unshielded Twisted Pairs (UTP), especially in homes and offices. For UTP, Ethernet currently supports four data rates: 10 Mb/s (10BASE-T), 100 Mb/s (100BASE-TX), 1 Gb/s (1000BASE-T) and 10 Gb/s (10GBASE-T). For 100 Mb/s and higher data rates, Ethernet physical layer transmitters transmit continuously to keep transmitters and receivers aligned. When there is no data to send an auxiliary signal called IDLE is sent. This means that most of the elements in the interfaces are active at all times leading to an energy consumption that is large and independent of the traffic load.

To reduce energy consumption, the IEEE 802.3az standard introduces the concept of Low Power Idle (LPI) which is used instead of the continuous IDLE signal when there is no data to transmit [7]. LPI defines large periods (T_q) over which no signal is transmitted and small periods (T_r) during which a signal is transmitted to refresh the receiver state to align it with current conditions. The operation of the LPI mode is illustrated in Figure 1. The energy consumption of a physical layer device (PHY) when it is in LPI mode is expected to be significantly lower than when it is in the active mode. This has been confirmed for the case of Network Interface Cards (NICs) where reductions of 70% in the power consumption of a 1Gb/s NIC have been reported in [16].

The actual energy savings on a given link depend on the amount of time that the link spends in LPI mode. This time can be reduced by the transition overheads associated with activating (T_w) and putting it into LPI mode (T_s). During those transitions, there is significant energy consumption and the transition times are large compared with the frame transmission time [9],[16]. The transition times for the different speeds are summarized in Table I and compared with the frame transmission times for a 1518 byte and a 64 byte packet. To measure the efficiency of EEE, the concept of Single Frame efficiency which measures the efficiency of EEE for single frame transmission is introduced. When a single frame is transmitted the link has to be activated to send a frame and then deactivated after the transmission. Therefore for a frame transmission time of T_f, the link is active or in transitions for $T_w+T_s+T_f$. The ratio of both times is defined as the single frame efficiency: $SF_e= T_f /(T_w+T_s+T_f)$. It can be observed that the values for the Single Frame efficiencies in Table I are low. This results in an energy consumption versus load profile that tends to saturate at medium or low loads unless packets are coalesced [9]. As an example, in [16] for a 1Gb/s link a 6% traffic load composed of evenly spaced packets was shown to prevent the link from entering into LPI mode altogether.

III. POWER CONSUMPTION OF ETHERNET SWITCHES

There is a wide range of Ethernet switches. From a four or five port switch used in homes and small offices to modular switches that support hundreds of ports and different transmission media [17]. Power consumption increases with the number of ports and their speed and therefore large switches consume much more energy than small ones. However since there are many more small switches than large ones, the aggregated energy consumption of the small switches to which users are connected is significant. For example the power consumption of small Ethernet switches in the US has been recently estimated in 7.9 TWh/year [18]. Small switches typically have 5,8,16 or 24 ports. This reduced number of ports enables highly integrated implementations in which only one [19] or a few integrated circuits are used [20]. The switch is composed of one physical layer device (PHY) per port, a switching fabric commonly implemented with a shared memory, control logic and a CPU [21].

The power consumption of switches and routers has been characterized in different studies [22][23][24]. The results show that once the router or switch is powered on and its ports are activated the power consumption is close to its maximum value. For example in [24] that value is around 90% of the peak power consumption for a core router and also for an Ethernet router. That means that only 10% of the peak power consumption is dependent on the traffic load. This is far from the proportional relation and results in poor energy efficiency as networks tend to be lightly loaded [25]. In [22] the energy consumption of commercial Ethernet switches is reported. In [23] an Ethernet based router for academic purposes was evaluated. In both cases the power consumption once all the ports are active is close to the peak power consumption. The power consumption is also analyzed when the number of active ports is varied. The results show that the power consumption increases as the number of active ports grows. To corroborate the results, the power consumption of an eight port Cisco Catalyst 3560-CG switch has been measured. The results are consistent with previous studies showing that only a very small percentage of the power consumption depends on the traffic load once all ports are active. Figure 2 illustrates the results in a single plot as to the measurement accuracy they were the same for no traffic and full traffic. This power consumption profile has motivated research efforts that try to reduce the number of active links when there is no traffic [15] or try to allocate traffic such that the number of links that are activated is minimized [14].

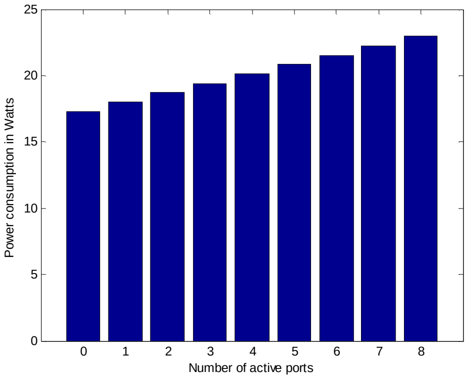

Figure 2 Energy consumption of a Cisco Catalyst 3560-CG switch as a function of the number of active ports

IV. POWER CONSUMPTION OF SMALL ENERGY EFFICIENT ETHERNET SWITCHES

To study how the use of Energy Efficient Ethernet affects the energy consumption profile of switches two small Ethernet switches have been characterized in a number of experiments. The models selected are D-Link DGS-1100-16 which is a 16 port Gigabit switch [10] and Level One GEU-0820 which is an 8 port Gigabit switch [12]. In this way two common configurations in terms of number of ports are tested. As mentioned before, the interest of analyzing small switches lies in the fact that their aggregated energy consumption is very significant [18].

In the first experiment, the power consumption is measured when the Energy Efficient Ethernet functionality is disabled and the number of active ports is varied under no traffic and full load conditions. As in the experiment with the Cisco Catalyst 3560-CG switch, the power consumption with no traffic and at full load was almost the same. The results for no traffic are shown in Figure 3 and can be directly compared with those of the Cisco Catalyst 3560-CG switch in Figure 2. It can be observed that the profiles are similar but the absolute power consumption of both the DGS-1100-16 and the GEU-0820 switches is substantially lower than that of the Cisco switch. This is a result of technology scaling and shows how the use of more advanced electronic technology can reduce the power consumption significantly. In particular the increment per port is lowered from 0.71 Watts to approximately 0.32 Watts. This power consumption reduction for 1000BASE-T PHYs has also been recently reported in NICs [16] when compared to previous studies [26]. It is also interesting to note that the power consumption of the GEU-0820 switch when no port is active is much lower than that of the DGS-1100-16 switch. This may be explained in part because the DGS-1100-16 switch has two times the number of ports in the GEU-0820 switch. However, the difference is so large that it suggests that the power consumption with no port active depends heavily on the switch implementation.

In the second experiment Energy Efficient Ethernet functionality is enabled and the same measurements done in the first experiment are repeated. For the case of full traffic load, the results are similar to those of the first experiment when EEE was disabled. The results for no traffic are shown in Figure 4. It can be observed that the profile changes significantly and becomes almost independent of the number of active links. This is a significant change as for light loaded networks, once EEE is adopted it would imply that there is little benefit in reducing the number of active links to save energy. However as discussed previously, large transition overheads have been observed in EEE [16]. This means that even for low loads, the energy consumption can be significant.

In the third experiment, the load of one of the ports was varied from 1Mb/s per port to 1Gb/s using 1518 byte or 64 byte packets. Those packet sizes are the best and worst cases for transition overhead in EEE. The goal of the experiment is to characterize the per port power consumption versus its traffic load. The results are shown in Figure 5 in terms of the percentage of power consumption for that port. It can be observed that the power consumption tends to saturate around 55 Mb/s for 1518 packets and well below 10 Mb/s for 64 byte packets. This is due to the transition overheads in EEE that are summarized for 1000BASE-T in Table I. When the sending rate is limited to a few Mb/s packets are sent spaced on the 1Gb/s link thus causing frequent transitions in and out EEE low power mode that reduce the energy savings. These results are similar to the behavior reported for an EEE NIC in [16]. Since the load of small switches is low, most of the time the switch would be in the left hand side of the plot where power consumption increases linearly with the load.

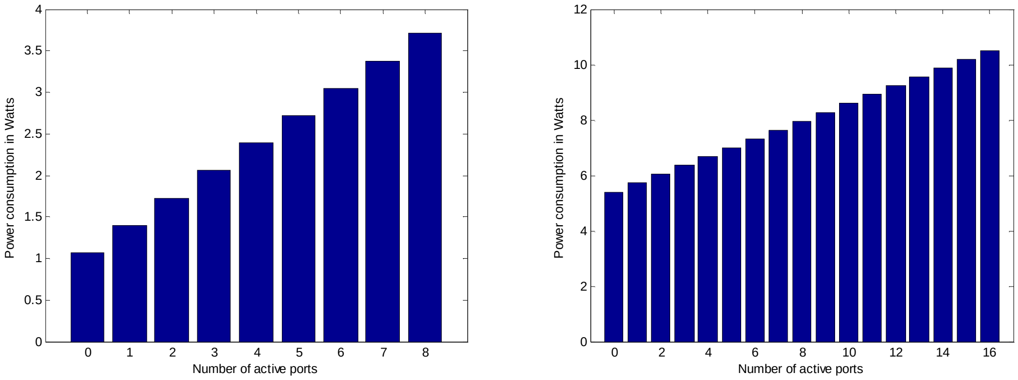

Figure 3 Energy consumption of Level One GEU-0820 (left) and D-Link DGS-1100-16 (right) switches as a function of the number of active ports with no traffic when EEE is disabled

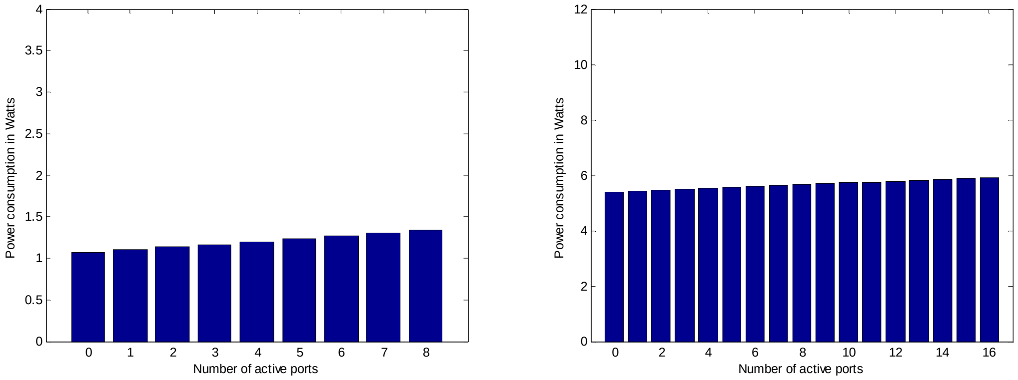

Figure 4 Energy consumption of Level One GEU-0820 (left) and D-Link DGS-1100-16 (right) switches as a function of the number of active ports with no traffic when EEE is enabled

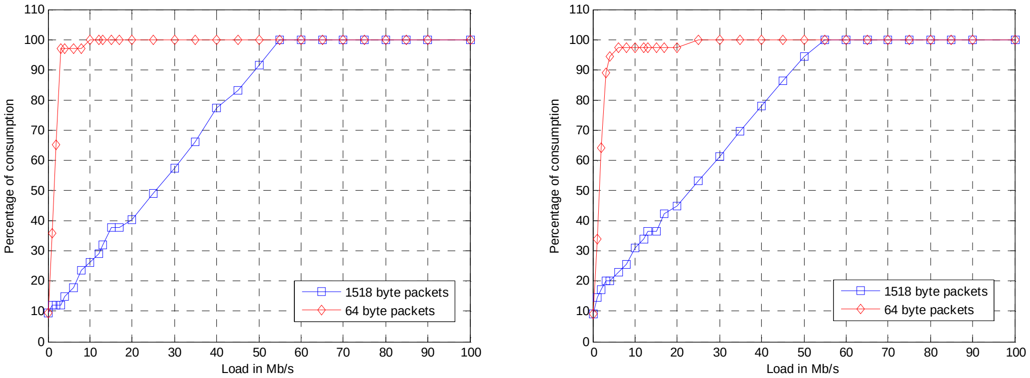

Figure 5 Energy consumption of a port in a Level One GEU-0820 (left) and D-Link DGS-1100-16 (right) switches as a function of the traffic load

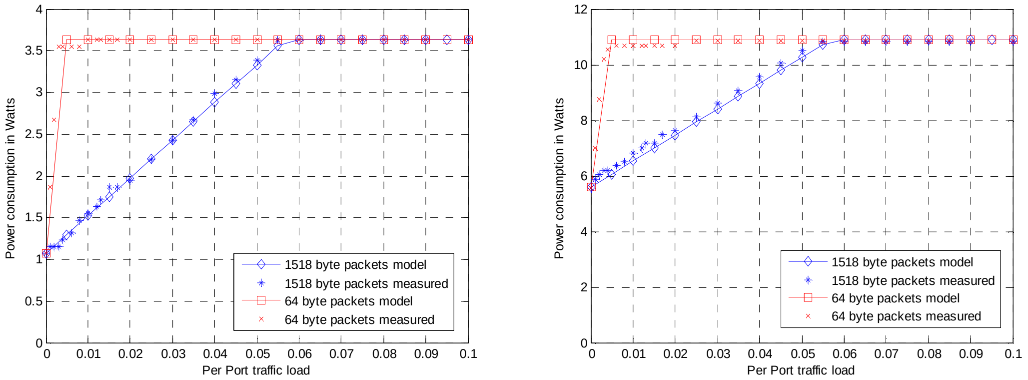

Figure 6 Energy consumption model for a Level One GEU-0820 (left) and D-Link DGS-1100-16 (right) switches as a function of the traffic load

V. AN ENERGY CONSUMPTION MODEL FOR SMALL ENERGY EFFICIENT ETHERNET SWITCHES

Based on the previous experiments, a model for the power consumption of small EEE switches can be proposed. Since the load for small switches is typically low, the model will focus on providing accurate energy consumption estimates for per port traffic below 50 Mb/s and a reasonable approximation for medium loads. The model is also conservative with regard to the traffic patterns and can be used to provide a lower bound on the expected energy savings.

One key observation for the model is that in many cases, traffic on the LAN is limited by a lower speed link, for example in the access to the Internet or in the interconnection with another LAN. When that is the case packets will be spaced when they are sent over that link so that for example at 50 Mb/s, 1518 byte packets are spaced by more than 200us due to the larger transmission times at low speeds. However when they reach the LAN their transmission time at for example 1Gb/s is only 12μs which means that they are sent isolated and each packet will cause an EEE mode transition with its associated overhead.

This suggests that for end user or Small Office/Home Office (SOHO) switches and PCs that send or receive traffic from the Internet it is reasonable to assume that each frame requires an EEE transition. This behavior is captured by the model.

The assumption of a lower link limiting the rate of the port is the same as that used in the third experiment. In that experiment it was observed that for low loads the power consumption increased linearly with the load. This is consistent which the fact that each packet requires an EEE transition and therefore the increase in energy consumption is directly proportional to the increase of bandwidth (and consequently to the number of packets). Therefore the power consumption in the proposed model is composed of a base power that is independent of the traffic load and a dynamic power that depends linearly on the traffic load.

Therefore proposed model is described by the following equation:

$$P = P_{base} + P_{dynamic}\sum_{i=1}^{Nport}\min(1, D\cdot\rho_i)$$

The parameters of the model are P_{base} which is the power consumption with no traffic load, $P_{dynamic}$ which is the difference between the power consumption at full load and P_{base} divided by the number of ports and D which is the increment in power consumption per increment in traffic load per port (ρ_i). D can be estimated from the measurements in the third experiment. For the switches evaluated, the value of D was close to 18 for 1518 byte packets so that power consumption saturated at a load of 55 Mb/s. For 64 byte packets, the value of D was much larger close to a value of 400. The value of D can also be estimated from the values of Table I. When packets are spaced, each packet requires $T_w+T_s+T_f$ seconds to transmit but only T_f contribute to the link load. Therefore the value of D would be $(T_w+T_s+T_f)/T_f$ which is precisely the inverse of the Single Frame Efficiency (SF_e) defined in Section II.

For a 1518 byte packet this gives a value of 17.6 and for a 64 byte packet a value of 390.2 both in line with the values estimated from the measurements.

The use of the model for the DGS-1100-16 and the GEU-0820 switches is illustrated in Figure 6 in which it is assumed that the link load is the same for all ports. The results of the model are also compared with the actual power measurements using different loads. It can be observed that they are in good agreement as in the experiment the load was controlled by limiting the transmission rate.

Obviously, the value of D depends on the traffic parameters such as the frame interarrival times and the frame size distribution. However as discussed before, for low loads and traffic sourced or destined to the Internet most frames will be transmitted isolated. When that occurs, D depends only on frame size and it can be estimated if the distribution of frame sizes is known. Let us assume that the probability of a frame having a size of L bits is p(L), then D can be calculated as follows:

$$D=\sum_{L=L_{\min}}^{L_{\max}}\left(p(L)\cdot\frac{1}{SF_e(L)}\right)=\sum_{L=L_{\min}}^{L_{\max}}\left(p(L)\cdot\frac{T_s+T_w+T_f(L)}{T_f(L)}\right)=$$
$$\sum_{L=L_{\min}}^{L_{\max}}\left(p(L)\cdot\frac{T_s+T_w+\frac{L}{R}}{\frac{L}{R}}\right)$$

where R is the link speed. For 1000BASE-T and 10GBASE-T links $T_w+T_s>>T_f$ and therefore D can be approximated as follows:

$$D\cong\sum_{L=L_{\min}}^{L_{\max}}\left(p(L)\cdot\frac{T_s+T_w}{\frac{L}{R}}\right)=R\cdot\left(T_s+T_w\right)\cdot\sum_{L=L_{\min}}^{L_{\max}}\left(\frac{p(L)}{L}\right)$$

where the influence of short packets on D can be clearly observed.

For end user systems, in many cases, most of the frames would also be 1518 byte frames or Acknowledgements that are correlated with data frames (an ACK reception triggers a frame transmission and the other way around). Therefore the isolated transmission of large frames can be a good approximation and in that case D would take a value of close to 18 for 1000BASE-T.

It is also worth mentioning that the proposed model is conservative in estimating the energy savings that is if the traffic patterns differ from the assumptions it would be only to increase the energy savings. Therefore the model can be also used to provide a lower bound on the expected energy savings when the assumptions on which is based are not fully met.

The model can be easily derived for other switches by measuring the maximum and minimum power consumption. Then P_{base} is the minimum power consumption and $P_{dynamic}$ is the difference between the maximum and minimum power consumption divided by the number of ports. This means that only two simple power measurements are required to use the model that then enables a fast estimation of energy consumption based on very simple traffic load and frame size measurements. This can be useful when considering the adoption of EEE in a LAN. Another interesting application of the model is to predict energy savings of techniques that are being proposed to improve energy efficiency, like energy efficient routing or dynamic link shutdown [14],[15].

VI. DISCUSSION

The Energy Efficient Ethernet standard addresses the energy consumption of the PHY devices but can also enable savings in other system components [27]. These possible additional savings would be achieved by putting those components in a low power mode when the ports are in LPI mode as in that case no packets can arrive until the PHYs are activated. It seems that all the additional savings are not achieved in the first generation of EEE switches as the power consumption when there is no traffic on any port although lower than in the legacy switch remains significant (close to 25% for Level One switch and around 50% for D-Link switch). One possible explanation is that vendors have focused on implementing EEE on this first generation and left the optimization of the rest of the switch elements for future releases. If that is the case one would expect further improvements in the future that will make the energy consumption of switches more proportional to traffic load. In any case, the proposed model would still be valid using different parameters (mostly reducing P_{base}). On the contrary, if there are actual limitations that make unfeasible a reduction of the power consumption when there is no traffic, then techniques that put the entire switch on a sleep mode such as the one proposed in [18] will provide significant benefits. On the other hand, techniques that only deactivate some of its links will provide insignificant energy savings in EEE switches.

Another interesting observation from the experimental results is that for no traffic EEE achieves a reduction of the port related power consumption of close to 90%. This means that the PHY consumption in LPI mode has to be around 10% that of the active mode in line with previous assumptions [9]. It is also worth mentioning the large decrease in power consumption due to technology scaling when comparing the D-Link and the Level One switches with the Cisco switch. This observation should be taken into account by network administrators as in some cases the energy cost reductions may justify the renewal of switches.

Finally, it is also interesting to note that the experiments confirm the potential of Energy Efficient Ethernet to significantly reduce power consumption for small switches under realistic user traffic conditions. The overheads caused by mode transitions are not an issue for today´s user traffic and should only be a concern for switches that have larger traffic loads, such as those used in Datacenters. In summary, Energy Efficient Ethernet will make the power consumption of small switches more proportional to system load helping to the more general goal of Energy Proportional Computing proposed in [4].

VII. CONCLUSIONS

In this paper the first evaluation of power consumption of EEE Ethernet switches has been reported. The experiments show how EEE can reduce the PHY power consumption by 90% when there is no traffic. Based on the results, a simple model for the power consumption of small Ethernet switches has been proposed. The model provides accurate estimations for low traffic loads. It can also be used as a lower bound on the expected energy savings in other cases. To use the model in a given switch only two simple power measurements are required.

As EEE is adopted over the next years, we believe that the model will be useful to estimate power savings in a simple way. Additionally the model can be used for research into new power saving techniques for Energy Efficient Ethernet LANs. For example, in the light of the model, the use of dynamic link shutdown seems to have much less potential than in legacy Ethernet.

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