Towards an energy efficient 10 Gb/s optical ethernet: Performance analysis and viability

D. Larrabeiti [a,*], P. Reviriego [b], J.A. Hernández [a], J.A. Maestro [b], M. Urueña [a]

[a] Universidad Carlos III de Madrid, Av. Universidad 30, E-28911 Leganés, Madrid, Spain
[b] Universidad Antonio de Nebrija, C. Pirineos 55, 28040 Madrid, Spain

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ABSTRACT

The new IEEE 802.3az Energy Efficient Ethernet (EEE) standard will improve significantly the energy efficiency of 10 Gbps copper transceivers by the introduction of a sleep mode for idle transmission times. The next step towards energy saving seems to be the application of similar concepts to Optical Ethernet, both for short and long range links. To this aim, this paper starts by proposing an analytical model to estimate the energy consumption of a link that uses a sleep-mode power saving mechanism. This model can be useful to answer a number of questions that need to be carefully studied. Otherwise, the complexity of optical components could be increased for the sake of an energy saving that could turn out negligible. In the rest of the paper we analyze three key questions to try to shed some light on this design decision: (a) is the new copper EEE actually outperforming the current regular optical Ethernet in terms of energy saving in such a way that optical PHYs (transceivers) actually need a *green* upgrade to remain more energy efficient than their copper counterparts? (b) How much energy saving could be actually achieved by EE optical Ethernet? (c) What is the transition time required to achieve a substantial energy saving at medium traffic loads on EE 10 Gb/s optical Ethernet links? The answer to the latter question sets a concrete goal for short-term research in fast on–off laser technology.

1. Introduction

The efficient use of energy in communications has become a major concern in recent years, not just because of environmental awareness but also for direct monetary costs for telecom operators, ISPs and network-based application service providers. This has triggered intense activity in standardization bodies and in industry on the quest for more energy-efficient designs of both computing systems and networked devices. Indeed, key research studies [1] show that Internet communication is particularly inefficient, even if compared to wireless transmission, and that the potential for improvement by means of energy-aware hardware and protocols is very high. Moreover, the absolute consumption figures – [1] estimated over 6 TWh/year in USA's Internet for the year 2000, not including cooling and UPS (Uninterruptable Power Supply) energy – and its expected growth advise to re-engineer the networks in an energy aware way.

Ethernet is a key technology in this global energy bill that can be made energy-efficient with important savings, estimated over 3 TWh/year for the year 2005 [2]. Two different media are commonly used in high speed Ethernet links: copper (TIA/EIA UTP cable categories 5 and 6, and ISO/IEC STP cable category 7) and optical fiber. In this paper we focus on 10 Gb/s Ethernet, for its superior power consumption and more challenging optimization. This rate is currently used by high-end servers, switches and core routers. Usually deployed within data centers, 10 Gbps copper Ethernet supports links of up to 100 m and

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* Corresponding author. Tel.: +34 916249953.
E-mail addresses: dlarra@it.uc3m.es (D. Larrabeiti), previrie@nebrija.es (P. Reviriego), jahgutie@it.uc3m.es (J.A. Hernández), jmaestro@nebrija.es (J.A. Maestro), muruenya@it.uc3m.es (M. Urueña).

is specified in the 10GBASE-T standard, whereas 10Gbps fiber Ethernet is employed in all scenarios. Each fiber type and range is covered by a different standard. In particular, the 10GBASE-SR standard targets short range fiber lengths and can be used in the same configurations as 10GBASE-T.

The Energy Efficient Ethernet (EEE) standard (IEEE 802.3az [3]) has already defined a mechanism for 10 Gbps copper transceivers that will improve significantly its energy efficiency. This mechanism is based on a low-power sleep-mode for idle transmission times between frame arrivals. The next logical step seems to be the application of a similar mechanism to Optical Ethernet, both for short and long range links. Bearing in mind that this will definitely increase the complexity of optical transceivers, it is important to analyze and quantify the expected benefits of such a design step and the technological requirements to make such benefits relevant. As we will show, this is not a straightforward question, as demonstrated by the authors in [4] for copper EEE, where the existing technological bounds for PHY waking/sleeping time impose a severe penalty to the energy saving at medium loads.

Toward this goal, in this article we firstly propose an analytical model to estimate the performance of a sleep-mode power saving mechanism. Then we analyze three key issues to try to shed some light on the potential and viability of EE Optical Ethernet: (a) is the new copper EEE actually outperforming the current regular optical Ethernet in terms of energy saving in such a way that optical PHYs actually need a *green* upgrade to remain more energy efficient than their copper counterparts? In other words, could EEE 10GBASE-T shift regular 10GBASE-SR off the market because of its more energy efficiency? (b) How much energy saving could be actually achieved by EE optical Ethernet? This will depend heavily on the sleep/awake transition time, made up of laser on–off time plus clock locking time in the case of awakening; therefore another key question is: (c) what is the transition time required to achieve a substantial energy saving at medium traffic loads on EE 10 Gb/s optical Ethernet links? Is it in the order of magnitude of on–off switching times of state-of-the-art lasers?

We address these questions in the following way. Firstly in Section 2, a simple analytical model to estimate the energy consumption of a link that implements a sleep-mode power saving mechanism is presented. Then we study question (a) in Section 3, and questions (b) and (c) in Section 4. This work develops and extends preliminary short contributions by the authors presented at OFC 2010 (poster) [5] and at Photonics in Switching 2010 [6].

2. An analytical model for the energy consumption of sleep mode power saving mechanisms

A number of analytical models have been proposed for different energy saving techniques. For example in [2] a Markov chain model was presented for the Adaptive Link Rate technique. In [7] a model for a complete router is introduced and [8] presents an analytical model for an energy saving technique for bundled links.

In this section an analytical model to estimate the energy consumption of a link that uses a two state (sleep/active) power saving mechanism is proposed. The behavior of a link that implements such a mechanism is as follows. When the link is idle and a frame arrives, some time T_w is needed before transmission can start. When there are no further frames to transmit, some time T_s is needed before the link gets switched to the sleep mode. If during a transition to the sleep mode a frame arrives, that transition must be completed and then the transition back into the active mode starts. This is in essence the mechanism defined in the EEE standard for 10GBASE-T links (this is illustrated in Fig. 5 in Section 3), except for an additional refresh signal detailed in Section 3.

Assuming that the transition times are multiples of the frame transmission times (denoted as T_f in the following), this could be modeled with a state machine in which state $S(i)$ represents the state in which there are i frame transmission times left to reach the low power state if no new frames arrive. $S(0)$ would correspond to the low power state. Then for example, if the link is in state $S(0)$ and a frame arrives it would transition to $S(w+1+s)$ where $w = T_w/T_f$ and $s = T_s/T_f$ are the number frame transmission times required for the wake and sleep transitions. The states $S(1)$ to $S(s)$ represent the sleep transition and therefore a frame arrival in those states would make a transition to $w+1+s$ states forward. However states $S(i)$ with $i > s$ represent states in which the link is active and therefore a frame arrival would make a transition only one state forward.

In order to compute the energy consumption, the time is divided into intervals of duration a frame transmission time. Then assuming that the frame inter-arrival times are exponentially distributed [9], the probability that i frames arrive for transmission during a T_f interval will be given by

$$P_a(i) = \frac{\rho^i}{i!} \cdot e^{-\rho} \tag{1}$$

where ρ is the load factor of the link. During that period the link would be able to transmit a frame if it is active.

Then assuming that the link was in state $S(i)$ at the beginning of the interval the following transitions will occur with probability $P_a(i)$ when $i > s$

$$\begin{aligned}
&S(i) \Rightarrow S(i-1) \quad \text{with } P_a(0)\\
&S(i) \Rightarrow S(i) \quad \text{with } P_a(1)\\
&S(i) \Rightarrow S(i+1) \quad \text{with } P_a(2)\\
&S(i) \Rightarrow S(i+2) \quad \text{with } P_a(3)\\
&\ldots
\end{aligned} \tag{2}$$

When $i \le s$ the following transitions will occur:

$$\begin{aligned}
&S(i) \Rightarrow S(i-1) \quad \text{with } P_a(0)\\
&S(i) \Rightarrow S(i+w+s) \quad \text{with } P_a(1)\\
&S(i) \Rightarrow S(i+w+1+s) \quad \text{with } P_a(2)\\
&S(i) \Rightarrow S(i+w+2+s) \quad \text{with } P_a(3)\\
&\ldots
\end{aligned} \tag{3}$$

The state diagram and transitions for the case $w = 5$ and $s = 4$ are illustrated in the Fig. 1 where the states are truncated in S14 and only some transitions are shown for clarity.

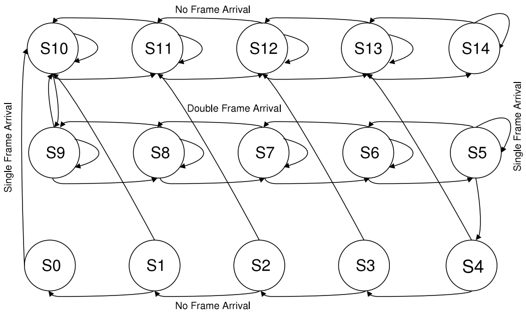

Fig. 1. State diagram of the proposed model for $w = 5$ and $s = 4$ showing only some state transitions.

In steady state the probabilities to transition in and out of each state should be equal. If the probability that the link is in state $S(i)$ is denoted as $P[S(i)]$ then for a state in which $i > s$ we have

$$P\left[S(i)\right] \cdot \left(P_a(0) + \sum_{i=2}^{\infty} P_a(i)\right) = P\left[S(i+1)\right] \cdot P_a(0) + \sum_{k=2}^{\infty} P\left[S(i-k+1)\right] \cdot P_a(k). \quad (4)$$

The equations for the other states can be obtained in a similar way. Solving the equations requires a truncation in the number of states and also in the number of frames that arrive in a time interval. Using (1) the truncation point for the number of frames can be selected without compromising accuracy, whereas for the number of states a sufficiently large value can be easily found.

The solution to the equations gives the probabilities that the link is in each $S(i)$ state. Then $S(0)$ gives the probability and therefore the percentage of time that the link is in low power state from which the computation of the total energy consumption (E) is trivial:

$$E = P\left[S(0)\right] \cdot E_{lp} + (1 - P\left[S(0)\right]) \cdot E_{\text{act}} \quad (5)$$

where E_{lp} is the energy consumption in low power mode and E_{act} the energy consumption in active mode and transitions.

The proposed model is an approximation as it splits the time in discrete time intervals and assumes that the transition times are multiples of the frame transmission times. Also, the model does not include the refresh periods defined in the EEE standard [3] detailed in Section 3. However the contributions of such periods to energy consumption should be small as discussed in [10]. To roughly evaluate the accuracy of the approximation we present three examples where the model is compared with results obtained by simulation.

In the first scenario the transition timers from the EEE standard for 10GBASE-T are used (about 5 μs to wake and close to 3 μs to sleep). The results are shown in Fig. 2 for different frame lengths. It can be observed that the approximation is good but with a small deviation at medium loads for large frames. This is due to the longer frame transmission times for large frames (1.2 μs for a 1500 bytes frame) that make worse the approximation of T_w and T_s being multiples of T_f.

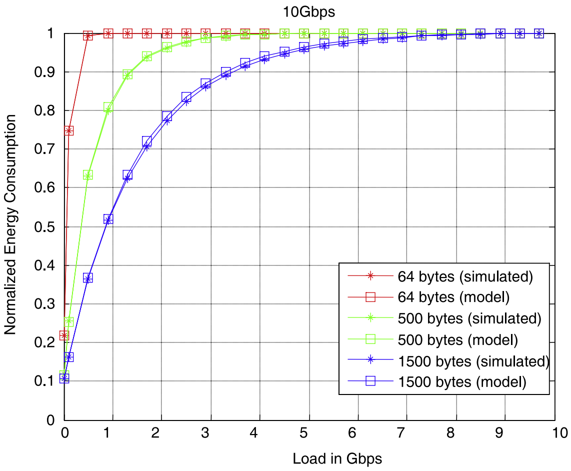

Fig. 2. Energy consumption (relative to active mode) estimated by the model (squares) and obtained by simulation (points) of a 10GBASE-T EEE PHY for small (64 bytes), medium (500 bytes) and large (1500 bytes) frames.

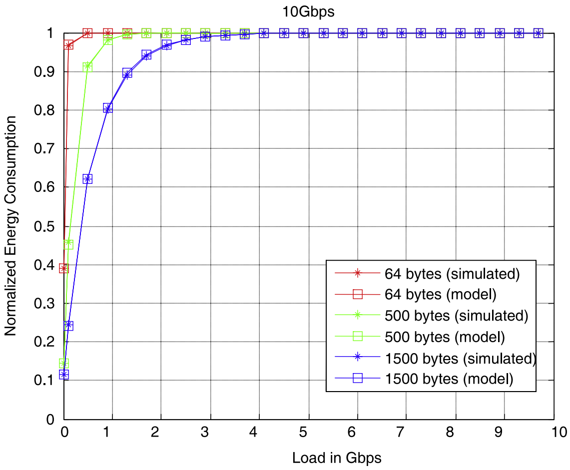

Fig. 3. Energy consumption (relative to active mode) estimated by the model (squares) and obtained by simulation (points) for a 10 Gbps link using $Tw = Ts = 10$ μs, for small (64 bytes), medium (500 bytes) and large (1500 bytes) frames.

In the second scenario, transition times $T_w = T_s = 10$ μs are used and the results are illustrated in Fig. 3. In this case the approximation is better as the transition times are larger.

Finally, smaller transition times ($T_w = T_s = 1$ μs) are used in the last experiment. In this case the approximation is worse as seen in Fig. 4. This again is due to the fact that the approximation that transition times are multiples of the frames transmission times is worse.

From the previous experiments, it becomes apparent that the model provides a good approximation to the values obtained in simulation when transition times are sufficiently large. For small transition times the model could be modified such that each state corresponds to a fraction of a frame transmission time. This modification implies that now a single frame arrival causes a transition to $n - 1$ states forward, where n is the number of time

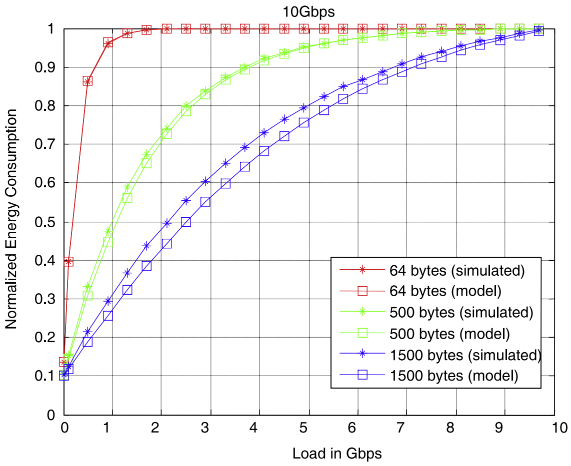

Fig. 4. Energy consumption (relative to active mode) estimated by the model (squares) and obtained by simulation (points) for a 10 Gbps link using $Tw = Ts = 1$ μs, for small (64 bytes), medium (500 bytes) and large (1500 bytes) frames.

fractions required to transmit a frame. Similarly if two frames arrive, a transition to $2n-1$ states forward is made and so on. Therefore, with those simple modifications, better accuracy could be achieved. However this extension of the model is left for future work since we consider it a sufficiently good approximation for design purposes. This analytical model can be useful to validate simulation results and to quickly estimate the energy consumption of a link without performing simulations. In the following sections, for the sake of clarity of graphs, only simulation results are shown as the focus is to discuss several design trade-offs and not to further evaluate the accuracy of the just-described model.

3. Comparison of EEE 10 Gbps Copper PHYs vs regular Fiber PHYs

10 Gbps Fiber PHYs currently require much less energy than copper PHYs. For example 10GBASE-SR PHYs are estimated to consume less than 1 W whereas early 10GBASE-T devices can consume more than 8 W [11]. This difference will tend to narrow in the future with newer generations of 10GBASE-T PHYs that are expected to consume less than 4 W [12]. However 10 Gbps copper PHYs will still consume more energy than their optical counterparts as they need to perform very complex signal processing operations in both the transmitter and the receiver. This discussion seems to suggest that 10Gbps optical PHYs will always be more energy efficient than copper PHYs. However the introduction of the EEE standard will greatly improve the energy efficiency of copper PHYs and backplane Ethernet PHYs, and since Fiber PHYs are not yet addressed by the standard, there will be a period of time during which copper PHYs may be a strong competitor of fiber PHYs in terms of energy efficiency. Let us examine this question.

As already described, the IEEE 802.3az Energy Efficient Ethernet (EEE) standard [3] tries to reduce energy consumption of Ethernet devices by defining a low power mode for inactivity periods essentially equivalent to the one described in Section 2. A PHY that has no frames to transmit can turn into a low power mode and, as soon as new frames arrive it is set back into the active mode very quickly (in a few microseconds). This enables energy savings that are rather transparent to upper protocol layers.

Fig. 5 depicts the way sleep and active modes work, and shows the different times specified in the standard to sleep and wake the PHY uni-directionally, and to refresh the parameters at the receiver while in sleep mode. The estimated savings while in low power mode can be close to 90% (see for example [10] for details on 10GBASE-T) and therefore, for links that spend most of the time in low power mode, the energy consumption is drastically reduced. This can mean that, for lightly loaded links, a copper PHY that implements EEE may be more energy efficient than an optical one. For example for a 4 W 10GBASE-T PHY if the link is in the low power mode 90% of the time the energy consumption would be $0.1 * 4\,\mathrm{W} + 0.9 * 0.4\,\mathrm{W} = 0.76\,\mathrm{W}$ that is in the range of what an optical PHY would consume.

However a recent performance evaluation of EEE [4] shows that the transition times in and out of the low power mode are significant and that even for low loads the link may spend little time in the low power mode as frames cause it to transition between modes continuously. For 10GBASE-T the times to enter and exit the low power mode are larger than 4 μs and close to 3 μs respectively [3]. This compares with a frame transmission time of 1.2 μs for a 1500 byte frame. In addition, during those transitions the PHY consumes a significant amount of energy.

To evaluate under which conditions an EEE enabled 10GBASE-T copper PHY would be more efficient than a fiber PHY, we have carried out simulations similar to those reported in [4]. As 10 Gbps PHYs are commonly used in links that aggregate traffic from many sources, it is a reasonable approximation to use a Poisson model for the frame arrivals as proposed in [9]. The results from this model would provide an approximation that can be used for an initial comparison with the optical PHY. In the simulations, the link is set into low power mode when there are no frames to transmit and back to the active mode as soon as a frame arrives for transmission. The transition times between modes are those of the standard [3]. Finally, to estimate the energy consumption

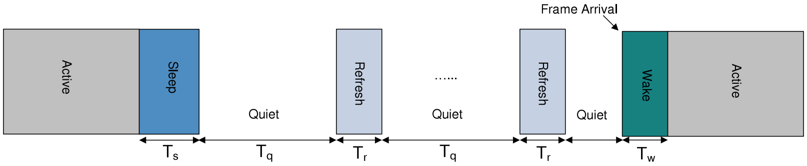

Fig. 5. Times involved in the Energy Efficiency mechanism defined in IEEE 802.3az.

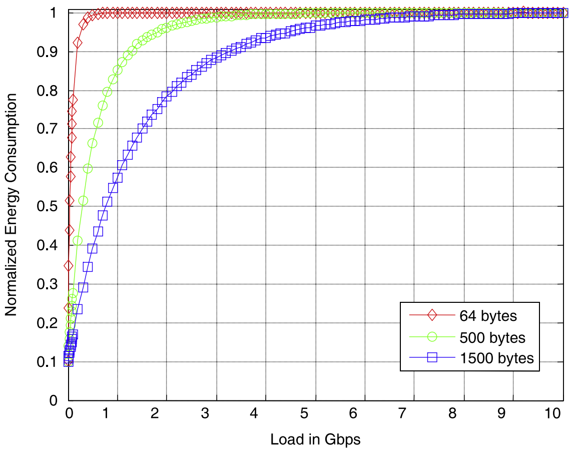

Fig. 6. Energy consumption (relative to the active mode) versus load of a 10GBASE-T EEE PHY for small (64 bytes), medium (500 bytes) and large (1500 bytes) frames.

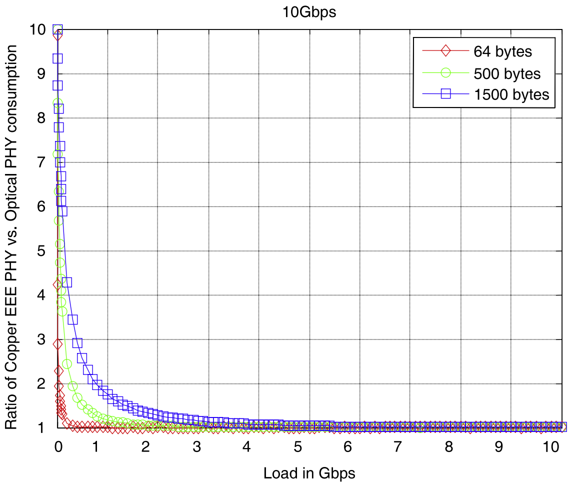

Fig. 7. Times that EEE 10GBASE-T (copper) power consumption in active mode can be larger than that of an optical PHY and still be more energy efficient.

it is assumed that there is significant energy consumption during the transitions and in the active mode, whereas the energy consumption in low power mode is only 10% that of the active mode. The results obtained are presented in Fig. 6 for small, medium and large frames. It can be observed that even for small loads the energy consumption approaches that of the active mode (a value of one). This is caused by the transition overheads and has a larger impact when small frames are transmitted.

Obviously the power consumption versus load in a practical configuration would depend on the sizes of the frames and the inter-arrival times, however the results presented try to cover the extremes (short and large frames); real traffic should have a power consumption in between these two (in Fig. 6 we show as a reference the data for 500-byte frames). This is further corroborated by the analysis of real data traces from different scenarios performed in [4] that showed that the power consumption gets quickly close to that of the active mode for relatively small link loads.

Making a preliminary comparison of power consumption of EEE 10GBASE-T vs optical 10G is not straightforward, because it is not possible to know in advance to what extent the vendors will be actually able to reduce the consumption on the active mode in the next generation of copper transceivers, and by this way get closer to their optical counterparts. However it is possible to estimate how many times the consumption of copper transceivers in the active mode can stand above the optical ones, and thanks to the EE sleep mode, be more efficient than those.

For this purpose, a relative measure will be used. This measure is the times that the copper PHY power consumption in the active mode can be larger than that of the optical PHY and still be more energy efficient because of the use of the low power mode. For example, when the load is close to zero the power consumption of an EEE PHY would be approximately 10% that of the active mode and therefore the PHY power consumption in the active mode can be up to 10 times greater than that of a fiber PHY and still be more energy efficient.

The results obtained for this ratio are shown in Fig. 7 for small, medium and large frames. It can be observed that the values tend quickly to one at small load values and therefore the EEE copper PHY would only be more energy efficient if its power consumption in the active mode is smaller than that of the fiber PHY. This is unlikely to occur in the near future as copper PHYs require much more complex processing than optical ones. In fact the use of EEE only helps significantly (ratios much larger than one) if the load is well below 1Gbps, that is, if the link is underutilized.

This leads us to the answer to our question (a). 10 Gbps Ethernet fiber PHYs will remain more energy efficient than copper PHYs even when EEE is implemented on the copper PHYs, except for links whose load is extremely low. For core network links, usually supporting sustained medium loads, the copper EEE PHY is not a competitor in terms of consumption. However, the energy saving of copper EEE should not be disregarded at all; it can be greater than fiber in scenarios where the traffic goes down drastically for long periods; for instance in corporate and campus LAN switches at night.

4. Performance analysis and viability of sleep-mode in 10 Gb/s Optical Ethernet

After analyzing the energy distance between copper EEE and regular optical transceivers, it is clear that embedding EE mechanisms into optical PHYs is an interesting feature that would permit these devices to keep on being more energy efficient than copper EEE PHYs at all traffic loads. Furthermore, optical transceivers need not send any refresh signal at all in low-power mode if burst-mode receiver technology [13] is used. This can yield very high energy saving, especially under low loads.

Now we focus on advancing the achievable performance of a hypothetical future optical EEE and on how different parameters affect this performance (questions (b) and (c) in this study respectively). This section is intrinsically speculative as no optical EEE standard is yet in place.

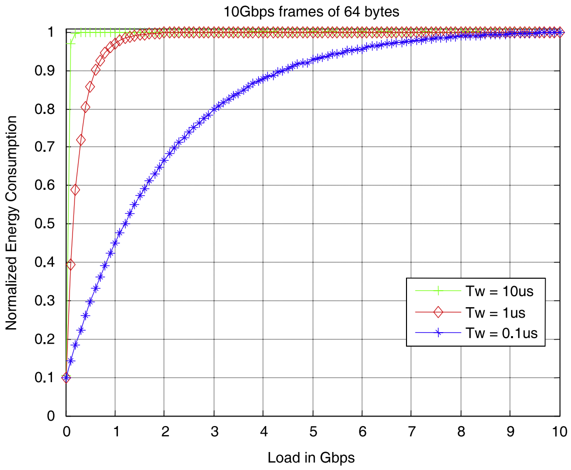

Fig. 8. Energy Consumption (relative to active mode) of 10GBASE-S EEE for 64-byte frames and different transition times (Tw).

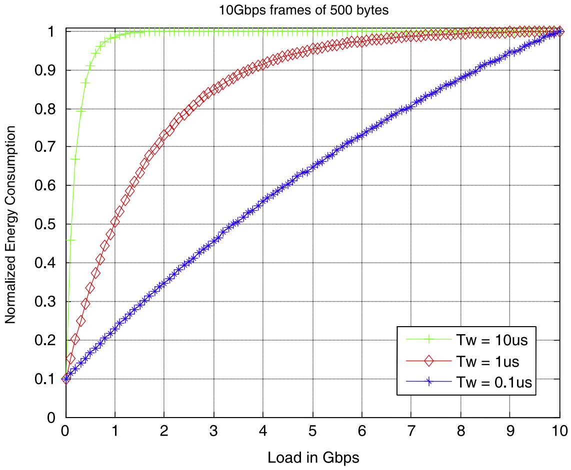

Fig. 9. Energy Consumption (relative to active mode) of 10GBASE-S EEE for 500-byte frames and different transition times (Tw).

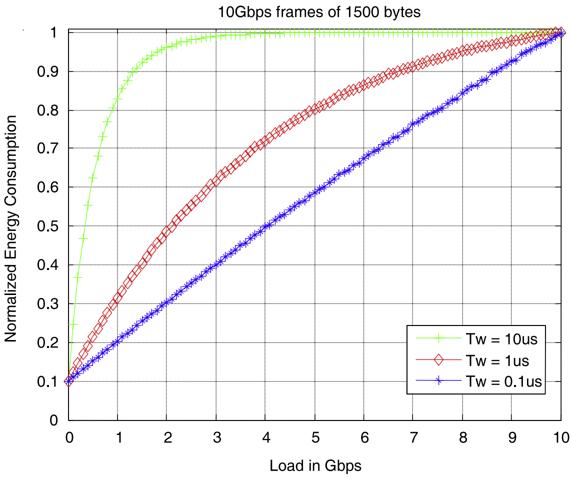

Fig. 10. Energy Consumption (relative to active mode) of 10GBASE-S EEE for 1500-byte frames and different transition times (Tw).

The performance in terms of energy consumption of the sleep-mode saving mechanism modeled in Section 2 depends on several factors such as: average frame size, transition time, low-power/high-power ratio and on frame scheduling. Assuming that frame size and frame scheduling cannot be altered, and given a fixed power ratio imposed by the technology of electronic components, a relevant design factor to consider is the transition time, which ideally should be negligible as compared to frame transmission time.

In copper EEE, if a new frame arrives the devices are activated and ready to send it in a few microseconds. This causes an added delay that is acceptable for most applications. In EEE there is significant power consumption when the device is active and during a transition, whereas the consumption in the low power mode is estimated to be an order of magnitude lower [10]. However, even though transition times are in the order of microseconds, they are comparable or even larger than frame transmission times. This can lead to significant energy overheads when isolated frame arrivals are frequent, as the link gets activated and deactivated just for sending one frame as noted in [4]. The use of low power modes in optical transceivers was discussed during the EEE standardization process [14]. The suggested transition times were in the range of 1–2 ms, in line with other studies [15] and much larger than those used in EEE for copper transceivers. This would imply that the use of a low power mode in optical PHYs could not provide good performance except for inactivity periods, as the transition time will be orders of magnitude larger than the frame transmission time. However, recent works suggest that the transition times could be drastically reduced if the optical transceivers are optimized for fast transitions [16]. This optimization may imply a more complex receiver – adopted from burst-mode receiver technology – and a higher power consumption in low power mode, as more elements on the transceiver are kept active to enable such fast transitions. Furthermore, extra components can be required to perform fast clock locking and make the preamble overhead negligible, e.g. [13].

In the following, we try to determine the expected performance with different transitions times. This is done by simulation so that there is no error due to the approximations in the model. These results can be used to find an optimal point in terms of transceiver complexity and transition times that maximize energy saving. Again, in order to analyze the performance the following assumption is made: the power consumption on idle mode is 10% that of the active mode and transitions. Given the 1.2 μs transmission time of a 1500-byte frame at 10Gbps, three transition times are evaluated: 0.1 μs, 1 μs and 10 μs. Initially exponentially distributed inter-arrivals are used as they can be a valid approximation for high speed Internet links [9]. The results are shown in Figs. 8–10 for different frame sizes: small, average and large. It can be observed that a transition time of 10 μs provides poor performance in all cases. Transition times of 1 μs show good performance for large frame lengths. Finally 0.1 μs would provide good performance for large and average frame lengths. From these data it becomes clear the answer to our original questions (b) and (c): taking as a design

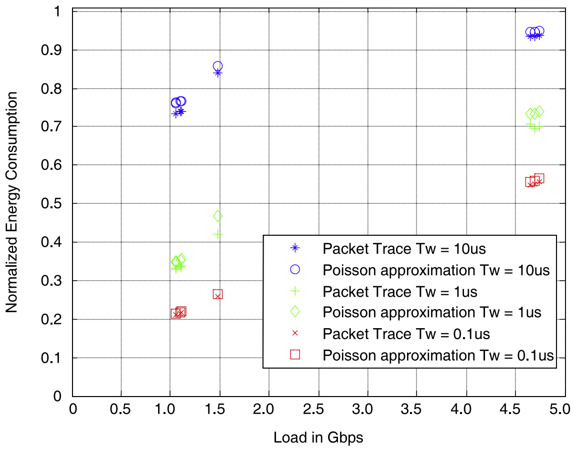

Fig. 11. Energy Consumption (relative to active mode) of 10GBASE-S EEE for real data traces with different transition times.

reference Fig. 9, transition times should be below 1 μs in order to obtain 90% to 60% of energy saving in the range 0%–20% of link load, and 90% to 5% in the larger range 0%–90%.

To further validate these results, we also carried out a number of simulations based on real traffic traces from a 10Gbps optical link. The monitoring equipment is located at the Equinix data-center in San Jose, CA, USA and is connected to an OC192 backbone link of a Tier1 Internet Service Provider (ISP) between San Jose and Los Angeles. This ISP has multiple OC192 links between these cities and the load balancing is done per flow. The traces are described in [17] and are available through CAIDA. The inter-arrival times and frame lengths in those traces have been used to compute the energy consumption in a sleep-mode-enabled transceiver. The results are shown in Fig. 11, which also includes the performance for exponential inter-arrivals. For the exponential inter-arrival simulations the frame size is the average frame size of each data trace and the arrival rate is the average number of frames per time unit in each data trace. In total eight traces are shown with loads ranging from 10% to close to 50%. It can be observed that the results obtained with the exponential inter-arrivals are a good approximation of the ones of the real traces for the different loads and transition times.

In the results presented so far, the dependency of the transceiver power consumption in low power mode with the transition time has not been reflected. As discussed in [16], one could expect the power consumption in low power mode to increase for the sake of a reduced transition time. To model this effect in a conservative way, in Fig. 12 the power consumption in low power mode is assumed to increase by 50% when the transition time is 1 μs and to double when the transition time is 0.1 μs. It can be observed that with this increase of energy consumption in low power mode, the use of lower transition times still provides large energy savings unless the link utilization is very low (below 1%). This shows that it makes sense to explore transceiver designs that reduce the transition times even if they substantially increase the power consumption in low power mode.

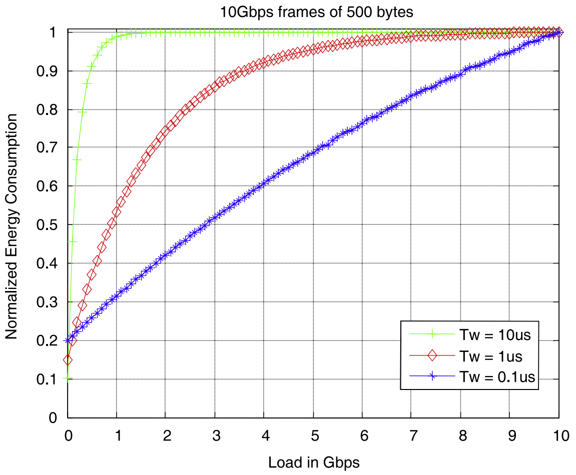

Fig. 12. Energy Consumption (relative to active mode) of 10GBASE-S EEE for 500-byte frames and different transition times (Tw) with a transition time-dependent power consumption in low power mode.

5. Conclusions

In this paper, we studied and provided answers to key questions on Energy Efficient Ethernet and its application to optical fiber PHYs. Firstly, we described a novel analytical model to estimate the energy consumption of a generic sleep-mode power saving transmission system, valid for both copper and fiber EEE, that adapts quite well to simulation results. This model can be used for Ethernet as well as other packet-based technologies. Then we determined under what circumstances IEEE 802.3az copper PHYs can outperform regular fiber PHYs in terms of energy saving. The results reveal that if the electronic technology of copper transceivers is able to make devices with an active power mode as low as two times the consumption of fiber PHYs, then copper PHYs with EEE can definitely outperform fiber PHYs in terms of energy consumption. However, due to the effect of transition times adopted by the standard for copper PHYs, the load range in which this may happen is very narrow (up to 5% of traffic load). This can still be interesting in certain scenarios where traffic goes down to almost zero for several hours. This scenario, not unusual in large company LANs, may justify by itself the effort towards an optical EEE even if the solution finally adopted is not as complex as the copper EEE. However, what actually makes optical 10Gb/s EEE a really promising enterprize is the huge relative energy saving that can be obtained not just at very low loads, but also at any load if transition times below 1 μs are achieved. In particular, if transition times under 0.1 μs were technologically feasible, the ideal linear behavior pursued by the Energy Efficiency movement (i.e. consumption proportional to utilization) is mostly accomplished. To this end, the research on fast on/off laser and fast clock locking technologies is paramount. Finally, our study shows that the use of a low power mode is beneficial, provided that low transition times can be achieved, even if that is at the expense of an increase in the low-power mode energy consumption. The results presented can be used to guide the design of optical transceivers optimized for Energy Efficiency.

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References

[1] M. Gupta, S. Singh, Greening of the internet, in: Proc. of ACM SIGCOMM, August 2003, pp. 19–26.

[2] C. Gunaratne, K. Christensen, B. Nordman, S. Suen, Reducing the energy consumption of ethernet with adaptive link rate (ALR), IEEE Transactions on Computers 57 (4) (2008) 448–461.

[3] IEEE P802.3az energy efficient ethernet standard, September 2010.

[4] P. Reviriego, J.A. Hernández, D. Larrabeiti, J.A. Maestro, Performance evaluation of energy efficient ethernet, IEEE Communication Letters 13 (9) (2009) 697–699.

[5] P. Reviriego, D. Larrabeiti, J.A. Maestro, J.A. Hernández, P. Afshar, L.G. Kazovsky, Energy efficiency in 10 Gbps Ethernet transceivers: Copper versus Fiber (poster) in Optical Fiber Communication Conference and Exposition OFC/NFOEC, 2010.

[6] P. Reviriego, D. Larrabeiti, J.A. Maestro, Would energy efficient ethernet be effective on 10 Gbps optical links? Photonics in Switching OSA Workshop, USA. July 2010.

[7] R. Bolla, R. Bruschi, F. Davoli, A. Ranieri, Energy-aware performance optimization for next-generation green network equipment, in: Proceedings of the 2nd ACM SIGCOMM workshop on Programmable routers for extensible services of tomorrow, August 21–21, 2009, Barcelona, Spain.

[8] W. Fisher, M. Suchara, J. Rexford, Greening backbone networks: reducing energy consumption by shutting off cables in bundled links, in: Proceedings of the first ACM SIGCOMM workshop on Green networking, August 30–30, 2010, New Delhi, India.

[9] T. Karagiannis, M. Molle, M. Faloutsos, A. Broido, A non-stationary poisson view of internet traffic, in: IEEE INFOCOM, 2004.

[10] D. Taich, J. Tellado, G. Zimmerman, O. Barkan, 10GBASE-T low-power idle proposal, presentation at the IEEE 802.3-EEE, May 2008 meeting.

[11] The green advantage of 10G optical fiber, Corning Cable Systems white paper LAN-1078-EN, November 2008.

[12] Aquantia to deliver world's first quad 10GBASE-T solution, Aquantia press release, May 2009.

[13] E. Kehayas, G.T. Kanellos, L. Stampoulidis, P. Bakopoulos, N. Pleros, G. Guekos, H. Avramopoulos, All-optical burst-mode receiver at 10 Gb/s, in: European Conference on Optical Communication, ECOC, 2004, Stockholm, Sweden, 2004.

[14] O. Haran, Applicability of EEE to fiber PHYs IEEE 802.3-EEE, September 2007 meeting.

[15] R. Kubo, J. Kani, Y. Fujimoto, N. Yoshimoto, K. Kumozaki, Proposal and performance analysis of a power-saving mechanism for 10-Gigabit-class passive optical network systems, in: Proc. Networks and Optical Conference and Optical Cabling and Infrastructure (NOC/OC&I) 2009, June 2009, Valladolid, Spain, pp. 87–94.

[16] S. Wong, L. Valcarenghi, S. Yen, D.R. Campelo, S. Yamashita, L. Kazovsky, Sleep mode for energy saving PONs: advantages and drawbacks, in: IEEE GLOBECOM Workshops, 2009.

[17] C. Walsworth, E. Aben, K.C. Claffy, D. Andersen, The CAIDA anonymized 2009 Internet traces, 15th January 2009. Available (online, February 2010): http://www.caida.org/data/passive/passive2009dataset.xml.