Improved Opportunistic Sleeping Algorithms for LAN Switches

M. Rodríguez-Pérez, S. Herrería-Alonso, M. Fernández-Veiga, C. López-García
Dept. of Telematics Engineering
ETSE Telecomunicación
Campus universitario s/n
36310 Vigo, Spain

Abstract—Network interfaces in most LAN computing devices are usually severely under-utilized, wasting energy while waiting for new packets to arrive. In this paper, we present two algorithms for opportunistically powering down unused network interfaces in order to save some of that wasted energy. We compare our proposals to the best known opportunistic method, and show that they provide much greater power savings inflicting even lower delays to Internet traffic.

I. INTRODUCTION

The total amount of energy needed to power networking infrastructure has been rising as more devices have been getting connected to the network. Moreover, the nominal link capacities have also been growing, demanding more and more power for the card transceiver with each speed increase. In the last few years, these greater power demands have coincided with increasing environmental concerns and higher operating costs associated with networking equipment.

Traditionally, the design of networking equipment concentrated in maximizing performance, irrespectively of power demands. However, as the operating costs associated with heat dissipation and energy consumption continue to increase, this trend is starting to reverse. This is not a big surprise, as other computer related fields, like computer processors, graphic cards, ..., also suffered this change in optimization focus not too long ago.

Many of the places where energy could be saved in the current Internet design were first identified in [1]. One of those places are the links where actual transmission takes place. Until recently, only power needs of mobile devices were devoted some consideration [2]. However, energy consumption in wired mediums cannot be neglected, when modern gigabyte cards already demand around 4 W and, soon to be the norm, 10 gigabyte cards consume in the order of tens of watts [3], [4], [5]. At the same time, most network interfaces sit unused most of the time wasting too much power [6]. For instance, even in highly-utilized backbone switches averaged traffic loads below 30 % are normal [7]. This is not only a problem to energy constrained devices, like laptops, but also a source of noticeable amounts of unnecessary heat for under-utilized switches.

In this paper we build on an opportunistic sleeping algorithm for powering down network interfaces when there is low probability of buffer overruns while the interface is down [3]. We analyze its shortcomings and propose several enhancements to the algorithm that greatly augment its power savings. Then, we simplify the resulting algorithm the most so as to increase the chances making it deployable in cheap hardware too. The result is an algorithm much simpler than the original, and that is able to achieve much higher energy savings with less added delay and a negligible increase of packet losses.

The rest of this paper is organized as follows. Section II shows the model on which we will build on. Our proposals are described and compared against the original Gupta-Singh [3] algorithm in Section III. In Section IV we present an evaluation of the performance of the different algorithms. Finally, our conclusions are laid out in Section V.

II. LINE CARD POWER MODEL

In this paper we assume that line cards and, more precisely, its individual interfaces can be put to sleep. This is in accordance with previous works in the subject [3], [6], [8] and the general trend in other related fields, such as in embedded devices or in desktop computers, where different system parts can be powered down at will to save power.

Network interfaces could theoretically offer a fine grained control over what parts of the hardware are active, their operating speeds, etc. to adjust power consumption to our needs. This control could be exposed to the operating system via different sleeping profiles akin to those presented by ACPI [9]. We restrict ourselves to a simpler design with just one sleeping state where the network card is completely shut down without even the ability to sense the line for incoming traffic. This permits maximum savings for the interface receiving part.

We will thus consider four operating states with different associated power profiles for a network card: one sleeping state, two awake states and a transitioning state from sleeping to active. The two awake states differ in the use of the transceiver port. This port can be either active, when the card is transmitting or idle, if the card is not doing useful work. Although we could define more than one transitioning state we ignore all but the one from sleeping to awake. All the other transitions can take place almost instantaneously and without incurring in additional power consumption, but the transition from sleeping to awake needs that the clocks of the two link endpoints network cards be resynchronized, and this
takes some time and needs as much power as that needed for active transmission, so we cannot simply ignore it.\(^1\)

We therefore define the following power consumption vector for a given interface: \(\bar{p} = \{p_a, p_i, p_h\}\), where \(p_a\) is the power consumption when the interface is actively transmitting data, \(p_i\) is the power drain when the interface is idle, and, finally, \(p_h\) is the (small) power drain while the interface is sleeping. Recall that \(p_a\) is also the power needed while transitioning from sleeping to awake.

### III. Opportunistic Sleeping

For an opportunistic sleeping algorithm to be defined, three are the questions that must be answered:
- When to sleep
- How long to sleep
- When to wake up

Throughout this section we will first describe the algorithm proposed by Gupta and Singh in [3] and then we will present our enhancements to it with their motivations.

#### A. The Gupta-Singh Algorithm

In [3] the authors present two related algorithms that give answer to the three aforementioned questions. We will concentrate only on the second algorithm one, as it provides greater savings than the first.

Their method relies on the assumption that packet arrivals to an Internet queue follow a Poisson distribution in small timeframes [10]. So they employ the average inter-arrival time of the last few packets (5 in their implementation) to obtain a rough estimation of the arrival process rate \((\lambda)\) in the short term.

When the queue occupation \((q)\) goes below a certain threshold \(b\), this information is used to estimate the time that the interface can be put to sleep \((t_s)\) without risking that the buffer occupation goes above \(b\). For this, the random variable \(X_k\) is defined as the sum of \(k\) independent and identically distributed exponential distributions with rate \(\lambda\), where \(k\) is the spare capacity in the queue below \(b\), that is \(k = b - q\). In effect, \(X_k\) is just an Erlang-k(\(\lambda\)) distribution, and the sleeping time is calculated so that

\[
P(X_k \geq t_s) \geq 0.9. \quad (1)
\]

That is, there is a relatively small chance (10\%) that the queue occupation will grow above \(b\) while sleeping. In their paper they propose to calculate \(b\) as a small fraction of the total transmission queue size \((B)\), for example \(b = 0.1B\).

If \(t_s\) results to be greater than the transition time \((t_d)\) the interface is put to sleep for \(\max(t_s - t_d, t_{max})\), with \(t_{max}\) being a configuration parameter. At the same time, the sender communicates this value to the receiving interface so that it can also enter the sleeping mode.

Once the sleeping timer fires, the interface resumes normal activity unless the queue happens to be completely empty

\(^1\)The resynchronization phase involves, in effect, the transmission of known signals to properly adjust the clocks. This transmission length is by no means negligible, and also consumes a non trivial amount of power.

\(q = 0\). In this case, a new sleeping interval of the same length is started. The receiving interface notices this new sleeping interval as it senses the line when its own sleeping timer expires and, as it measures no power it infers that a new sleeping interval has started and returns to the sleeping state.\(^2\)

A concise drawing depicting the state diagram of the algorithm is represented in Fig. 1.

#### B. Enhanced Gupta-Singh

We found some shortcomings in the previous algorithm that motivated us to try to improve it and measure the differences.

For instance, the Gupta-Singh algorithm introduces unneeded delays when it decides to sleep if there is still traffic in the queue. There is no reason for not postponing the sleeping interval until there is no more traffic in the queue, as all the time needed for emptying the queue will be used for profitable work. Furthermore, if during this time, the incoming rate remains low enough so that the queue finally drains, the new sleeping time will probably be larger, as there will be more room in the queue to allocate packets while sleeping. Recall also that the system losses work every time it transitions to active state as there is a period of activity, the transition time, in which no useful work is done, but the power consumption is high. So it is more profitable to sleep once a long interval than several short ones.

With this simple change, only sleeping when the queue is completely empty, we were able to vastly improve the total sleeping time of the interfaces. Moreover, the computation complexity needed for calculating \(t_s\) is greatly reduced.

In general, for solving \(t_s\) in (1) the following equation must be solved

\[
1 - \sum_{n=0}^{k} \frac{e^{-\lambda t_s} (\lambda t_s)^n}{n!} \geq 0.9,
\]

\(k\) being the number of packets that we can accommodate while sleeping. Sadly, there exists no closed form formula for \(t_s\) and we must resort to numerical approximations. In fact

\(^2\)If the receiving card can sense the line while sleeping the last two questions, how long to sleep and when to wake up, converge into one. Whenever the upstream interface decides to recommence the transmission the receiver notices that there is again power in the line and wakes up. On the other hand, if the receiving card does not have this capability, the sender must restrict itself to only transmit when there is a change that the receiver can detect it. That is, when its sleeping timer expires.
the Newton method gives good results in just a few iterations taking \( k\lambda^{-1} \) as the starting point. However, it is not practical for the network interface to solve this equation every time \( \lambda \) or \( k \) changes, that is after each packet arrival or departure.

The good news is that \( P(X_k \geq t_s) = f(\lambda t_s) \), as a fast inspection of eq. (2) soon reveals. So, for any fixed value of \( k \) the relation between \( t_s \) and \( \lambda \) becomes linear. With our simpler approach, that only sleeps when the buffer is empty, \( k \) remains constant (in fact, \( k = b \)). Therefore the network card operator can pre-load any pair \((\lambda, t_s)\) adequate to the buffer size and the card itself can easily extrapolate values for different packet incoming rates.

A second shortcoming is that the Gupta-Singh algorithm tries to maximize the total sleeping time as a way to maximize power savings. While both concepts are greatly correlated, sometimes putting an interface to sleep has predictable bad consequences in power consumption. There is certainly a minimum sleeping interval, below which it is not profitable to sleep. Quite the contrary, recall that once the sleeping interval finishes, the interface goes through a transitioning phase when power consumption is like that of active transmission. So, the total energy consumed during the sleeping interval becomes \((t_s - \delta)p_a + t_\delta p_a\). Before deciding to sleep, this quantity must be compared against the energy consumed if the interface was awake, but idle, for the sleeping interval duration. Thus

\[
(t_s - \delta)p_a + t_\delta p_a < t_s p_i
\]

or, in a more direct form,

\[
t_s > t_\delta \frac{p_a - p_s}{p_i - p_s}, \tag{3}
\]

becomes a necessary condition for a worthy sleeping interval. In the evaluation section we will show how this seemingly trivial change can have a dramatic effect in total energy savings.

With the above mentioned changes the new state diagram for the sender looks like the one represented in Fig. 2. The receiver algorithm remains unchanged.

C. A More Streamlined Proposal

After performing the previous adjustments to the pristine Gupta-Singh algorithm we tried to simplify even more the algorithm to improve its chances of being deployed.

For instance, is it possible to just try to sleep every time the queue gets empty? After all, our modifications demanded this condition to be met and then calculated an estimation of the maximum sleeping time based on the short time incoming rate. If this rate was low enough, then the calculated \( t_s \) would be high enough to sleep. In hindsight this should be usually the case, as the queue drains for a reason: the incoming rate is low. So, in our simplified proposal, the interface sleeps every time the queue empties.

Second question is how long to sleep. For this, eq. (3) already provides a lower bound. It is not worth to sleep less than the minimum provided by eq. (3). We take this minimum as the sleeping interval.

The final question is when to wake up the interface. Every time the sleep timer fires the upstream interface measures its transmission queue length. Although at first sight it may seem that the interface should transition to active whenever the queue is not empty, this is not very sensible, because if \( q \) is too small it will be put to sleep again in a too short time, making the transition to active and back to sleep unprofitable. It is better to queue some traffic so that the costs associated with bringing the interface back to active are small compared to the cost of transmitting the queued packets. With these considerations the minimum queue length for waking up \( (q_w) \) must meet that

\[
p_a \frac{q_w}{C} = p_a t_\delta, \tag{4}
\]

that is

\[
q_w = Ct_\delta, \tag{5}
\]

where \( C \) is the nominal interface bandwidth.

This condition also helps us to give suggestions about the minimum transmission buffer size \( (B) \), as it must be big enough to hold at least \( q_w \) packets while sleeping. A good approximation can be to make \( B \) an order of magnitude higher than \( q_w \). This way, the chance of overflowing the buffer capacity while sleeping is diminished.

The final state diagram for this simplified algorithm is represented in Fig. 3. Additionally, in table I we show a summary of the conditions used by the three described methods.

IV. EVALUATION

We performed via simulation a comparison between our proposed algorithms and the original Gupta-Singh proposal. For this we have employed the same dataset that they used

\[\text{Obviously, there should be some upper bound to the time spent sleeping with queued traffic so as to prevent starvation in the queue and too big delays.}\]
in their original paper [3], which they kindly provided to us. The data consist on the arrival times of packet in their internal network. Sadly, the data lacks packet sizes, so, for our study we have decided to initially consider a constant packet size of 1 000 bytes. We then made use of the ns-2 simulator to test our sleeping procedures in a gigabyte link [11]. For the sake of space we will only present here the results for two of the data traces: the one with most activity (labeled High in the following figures) with an occupation factor \( \rho = 7.2\% \), and, correspondingly, the one with the least (Low), with \( \rho = 0.13\% \).

For the power vector we use the same values as in [6], that is, \( p_a = 2 \text{ W}, p_1 = 1 \text{ W} \) and \( p_b = 0.1 \text{ W} \). In any case, the difference between \( p_a \) and \( p_1 \) matches that provided by some network equipment providers [12].

For the rest of the parameters, we decided to take the same values as in [3] to provide the fairest comparison. So that \( t_s = 0.5 \text{ ms} \) and \( t_{max} = 2.5 \text{ ms} \). We also set \( b = 0.1B \) for both the original Gupta-Singh algorithm and our modified proposal. Finally, the minimum profitable sleeping interval for our modified algorithms, is then \( t_s \left( \frac{p_a-p_b}{p_b} - 1 \right) \). The only remaining parameter, needed for the streamlined algorithm is \( q_w \). For a gigabyte interface and a packet size of 1 000 bytes, \( q_w = 62.5 \) packets.

All the experiments were done for different queue lengths, from the very short size of just \( B = 25 \) packets (\( b = 2.5 \)) to \( B = 350 \) packets. It is important to note that for the streamlined proposal, \( B \) should be much greater than \( q_w \), so experiments with queues smaller than 63 packets, although represented for completeness, are not significant.

The first three figures represent the percentage of time spent active, sleeping and transitioning for the three algorithms. Fig. 4 plots the total time spent in sleeping state. The upper figure shows results for the high traffic trace, while the lower one presents the results for the low traffic case. Results are similar, in any case. The streamlined algorithm shows almost constant values for all buffer sizes, however for very low buffer sizes this comes with the cost of very high packet losses, as we will later show in Fig. 9. Both Gupta-Singh and our enhanced proposal get better results as the buffer, and thus \( b \), increases. This is expected as \( t_s \) depends in the size of \( b \). The difference between both methods come from the fact that the enhanced proposal sleeps for longer periods as it waits for the queue to empty before sleeping.

Finally, the minimum profitable sleeping interval for our modified algorithms, is then \( t_s \left( \frac{p_a-p_b}{p_a} - 1 \right) \). The only remaining parameter, needed for the streamlined algorithm is \( q_w \). For a gigabyte interface and a packet size of 1 000 bytes, \( q_w = 62.5 \) packets.

### Table 1

<table>
<thead>
<tr>
<th>Sleep Condition</th>
<th>Gupta-Singh</th>
<th>Enhanced Gupta-Singh</th>
<th>Streamlined Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q &lt; b )</td>
<td>( t_s P (X_{b-q} &lt; t_s) \geq 0.9 )</td>
<td>( t_s P (X_b \geq t_s) \geq 0.9 )</td>
<td>( q = 0 )</td>
</tr>
<tr>
<td>( t_s &gt; t_s )</td>
<td>( t_s P (X_{b-t_s} \geq t_s) \geq 0.9 )</td>
<td>( t_s P (X_{b-t_s} \geq t_s) \geq 0.9 )</td>
<td>( q = 0 )</td>
</tr>
<tr>
<td>Sleep Interval</td>
<td>( \max(t_s - t_s, t_{max}) )</td>
<td>( \max(t_s - t_s, t_{max}) )</td>
<td>( \max(t_s (\frac{p_a}{p_b} - 1), t_{max}) )</td>
</tr>
<tr>
<td>Wake-up Condition</td>
<td>( q &gt; 0 )</td>
<td>( q &gt; 0 )</td>
<td>( q &gt; q_w )</td>
</tr>
</tbody>
</table>

Figure 3. Streamlined proposal.
is very costly.

Fig. 6 shows the total time in active state. This is similar for the three algorithms and very close to the real occupation factor of the traffic traces. This is expected for our proposals, as the exit from this state is based in a similar condition: the queue being empty. The original Gupta-Singh is even more aggressive existing active state, but this comes at the cost of shorter sleeping intervals and, correspondingly, much more transitions.

The real energy savings are depicted in Fig. 7. This come from comparison with the power a card that never enters sleeping state would draw. Note how, in spite of its simplicity, the streamlined algorithm reaches the highest savings of the three methods and is only comparable to the more complex enhanced proposal. At the same time, it is important to note that the Gupta-Singh algorithm can have pernicious effects on energy consumption in some scenarios. For example, notice how for the high-traffic scenario for small queue lengths it consumes more power than a non power-managed Ethernet card.

The last two figures show the performance cost that these power-management methods have. Fig. 8 shows the effects on average packet delay. As expected the delay increases with the buffer size. Note that for the Gupta-Singh algorithm this delay can reach very high values if the conditions for sleeping are favorable, that is, when there is very light traffic, as it can enter the sleeping state even with traffic in the queue. For both enhanced proposals this is not the case, as the sleeping interval is constrained to $t_{max} = 2.5 \text{ ms}$ and the sleeping interface is not reentered if there is traffic in the queue. This limit is clearly identifiable in the figure.

Finally, Fig. 9 shows packet drops suffered because of the sleeping methods. The streamlined proposal has very high-losses for very small buffers, but this was expected as there is a minimum sensible value for $B \gg q_w = 62.5 \text{ packets}$. In fact, from $B > 1.5q_w \approx 100 \text{ packets}$, packet drops are

---

4 Although packet losses where not taken into account, their eventual retransmission can increase energy consumption. However, as we will show in later figures, packet drops caused by the sleeping algorithms are low enough to warrant any further consideration.
comparable. In any case, for sensible $B$ values packet drops are nearly negligible. In fact we could not register losses with the sample traces for any buffer size greater than 225 packets with neither method.

V. CONCLUSIONS

This paper provides new algorithm for exploiting low traffic load patterns commonly found in Ethernet switches and endpoints. We first analyzed a well known opportunistic sleeping algorithm in [3]. In it, its authors propose an algorithm for shutting down transceivers so as to save power when there is low load in an Ethernet link.

In our analysis of their proposal we found several shortcomings. Among those, that the amount of introducing additional delay can be very high when the traffic load is too small and, even more importantly, that energy savings are not assured. In fact, under some circumstances the algorithm consumes more energy than an Ethernet port running no power management algorithm at all. This is due to too short sleeping intervals that draw more energy than the energy saved while sleeping.

Based on our findings, we provided two alternative algorithms. One directly based on the one in [3] and a second one that provides even slightly higher power savings with lower computational complexity. We believe that a form of either of both proposals can be easily implemented in Ethernet hardware for power savings of around 75% with respect of a non-power aware Ethernet card for typical workloads.

ACKNOWLEDGMENTS

We wish to thank Dr. Singh from Portland State University for kindly providing us with the traffic traces employed in his original study.

This work was supported by the “Ministerio de Educació y Ciencia” through the project TSI2006-12507-C03-02 of the “Plan Nacional de I+D+I” (partly financed with FEDER funds).

REFERENCES