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A note on the potential energy savings by extending the average cycle times in Passive Optical Networks

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(Invited Paper)

Abstract— **This article proposes a mechanism to increase the energy efficiency of the upstream channel in TDM-base PONs. Essentially, the ONUs are encouraged to accumulate traffic and transmit data bursts just by increasing the cycle time values artificially. The guard time is enlarged to avoid the case where ONUs are queried by the OLT and have none or few packets to transmit, thus allowing more time to sleep until the next cycle time. This strategy has however the downside effect of a substantial increase in the queueing delay experienced by packets. We provide a basic analysis to maximise the power savings for a given average delay target experienced by the packets.**

I. INTRODUCTION

Passive Optical Networks (PONs) have been proposed in the literature to open up the access bottleneck of DSL solutions. The Ethernet PON and Gigabit PON standards, currently deployed by many network operators, allow 1Gbit/sec of upstream bandwidth shared between up to 32 end users via TDM. A number of arbitration algorithms for the TDM sharing of the upstream channel have been proposed in the literature, being IPACT the most widely accepted by the research community.

In IPACT, the Optical Network Units (ONUs) send a Report message to the Optical Line Terminal (OLT) in the central office asking for a transmission window for the next cycle time. The OLT collects all report messages from the ONUs and assign non-overlapping transmission slots to the ONUs in a dynamic manner.

Previous studies have analysed IPACT from a teletraffic theory [1], showing that the average cycle time shows a steady-state behaviour only dependent on the total offered load and the guard time between consecutive transmission windows. Energy savings can be achieved if every ONU is provided with a sleep mode that can be used between its transmission windows, that is, while other ONUs transmit their own data [2].

The waking up times proposed in the literature to wake up a given ONU are in the order of $125\mu s$, thus requiring cycle times substantially above that number to achieve some energy efficiency [2], [3]. However, the cycle times at low loads for a moderate number of ONUs are often within a few tens of microsecs, hence bringing very poor (sometimes none) energy efficiency results.

To increase the energy efficiency, this work proposes to increase the inter-ONU guard time to force the creation of long cycle times. The consequence of this strategy is that the ONUs accumulate packets for longer times, thus transmitting their traffic in bursts and creating longer periods of time where the ONU may switch to the sleep mode and save energy consequently. This idea is inline with [4], [5], [6], [7].

The drawback of this strategy is that packets may suffer large queueing delays while they wait for the next cycle time. We also show the trade-off between energy savings and packet delay to help the OLT decide the appropriate inter-ONU guard time that achieves large power savings at moderate packet delay.

II. PROBLEM STATEMENT

A. Performance review of TDM PONs

Fig. 1 shows the time sharing of the upstream channel in a typical TDM PON. Essentially, a number N of ONUs send a Report message to the OLT asking for a transmission window V_i for the next "cycle time". After collecting all bandwidth demands from the ONUs, the OLT grants transmission windows to each ONU. In our case, we assume that each ONU is assigned as much bandwidth as it requested.

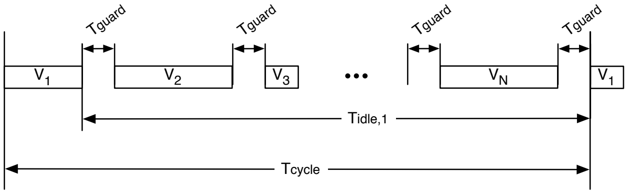


Fig. 1. A typical cycle time. Here, the V_i are the transmission windows of the ONUs.

We assume that each ONU collects packets to be forwarded upstream to the OLT following a Poisson process with rate λ_i, $i = 1, \ldots, N$. We further consider exponentially-distributed packet service times with mean:

$$E(X) = \frac{1}{\mu} = \frac{8 \times 1250 \text{ bits}}{10^9 \text{ bit/s}} = 10\mu s$$

that is, the average packet size is 1250 bytes.

Hence, let $\rho_i = \frac{\lambda_i}{\mu_i}$ refer to the traffic load offered by the i-th ONU ($i = 1, \ldots, N$) to the upstream channel. Clearly:

$$\rho_T = \sum_{i=1}^{N} \rho_i < 1 \tag{1}$$

i.e. total load must be less than unity.

As shown in [1], in the steady-state, the average transmission window $E(V_i)$ offered by the i-th ONU equals:

$$E(V_i) = \rho_i E(T_{cycle}) \quad \text{secs} \tag{2}$$

The average cycle time $E(T_{cycle})$ then follows:

$$E(T_{cycle}) = NT_{guard} + \sum_{i=i}^{N} E(V_i) \tag{3}$$

where $T_{guard} = 2\mu s$ refers to the gap between the transmission window of a given ONU and the next one (see Fig. 1).

Thus, solving eqs. 2 and 3 brings [1], [8] the steady-state average cycle time:

$$E(T_{cycle}) = \frac{NT_{guard}}{1 - \sum_i \rho_i} = \frac{NT_{guard}}{1 - \rho_T} \quad \text{secs} \tag{4}$$

Hence, the average transmission window for a given ONU (in the steady state is) is then:

$$E(V_i) = \rho_i \frac{NT_{guard}}{1 - \rho_T} \tag{5}$$

Under the assumption that all ONUs offer the same traffic load to the network, i.e $\rho_i = \rho_T/N$, then we have:

$$E(V_i) = \frac{\rho_T}{N} \frac{NT_{guard}}{1 - \rho_T} = \frac{\rho_T}{1 - \rho_T} T_{guard} \tag{6}$$

As shown in Fig. 2, the average transmission windows for an ONU is typically very small at low and medium traffic loads (often smaller than $6\mu s$).

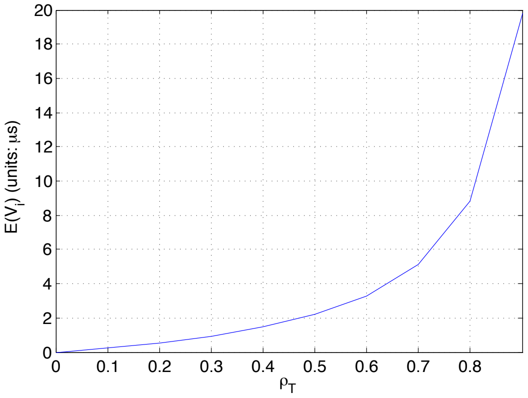


Fig. 2. Average $E(V_i)$

B. Analysis of the potential sleeping time of the ONUs

Following the previous analysis (and Fig. 1), the average amount of idle time, i.e. amount of time where an ONU may go to sleep until the beginning of the next cycle time, is:

$$E(T_{idle,i}) = E(T_{cycle}) - E(V_i) = \left(1 - \frac{\rho_T}{N}\right) \frac{NT_{guard}}{1 - \rho_T} \tag{7}$$

The next numerical example shows how much idle time can be achieved for a typical ONU.

Example 1 Consider a 1G-PON with $N = 8$ ONUs operating at total load: $\rho_T = 0.2$. Then, the average cycle time is:

$$E(T_{cycle}) = \frac{8 \times 2\mu s}{1 - 0.2} = 20\mu s$$

and the average transmission window for an ONU is $E(V_i) = \frac{0.2}{1-0.2} T_{guard} = 0.5\mu s$ only!! So, from the total $20\mu s$, a given ONU spends $0.5\mu s$ active and may go to sleep (and save energy) for $20 - 0.5 = 19.5\mu s$.

As shown in the example, at a given load, the idle time (waiting for the next cycle time) is a big portion of the cycle time, but stils a small quantity, since waking up the ONU requires about $125\mu s$ of time [2]. This can be shown in Fig. 3, where the average idle times at low and medium loads for a small number of ONUs is often very small and below the $125\mu s$ threshold that allows energy savings.

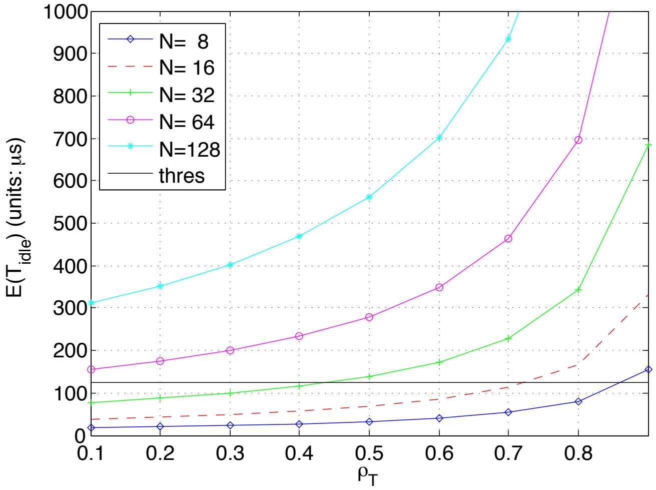


Fig. 3. Average Idle time for a given ONU

Hence, the goal is to increase the cycle time so that the ONU can go to sleep as much as possible and save power. This can be achieved by artificially increasing the value of T_{guard}.

Clearly, an increase in T_{guard} forces that ONUs accumulate packets for longer cycle times. This encourages the transmission of data bursts to the OLT, while allowing longer idle periods, that can be used to save energy. In what follows, we shall refer to T_{burst} rather than T_{guard} to emphasise the fact that this strategy produces bursty data transmission.

Example 2 Consider the previous 1G-PON with $N = 8$ ONUs operating at total load: $\rho_T = 0.2$. Now, consider that the inter-ONU gap is increased to $T_{burst} = 20\mu s$ (rather than the previous $T_{guard} = 2\mu s$). This strategy implies:

$$E(T_{cycle}) = \frac{8 \times 20\mu s}{1 - 0.2} = 200\mu s$$

and the average transmission window for an ONU is $E(V_i) = \frac{0.2}{1-0.2} T_{burst} = 5\mu s$. So, from the total $200\mu s$, a given ONU spends $5\mu s$ active and may go to sleep for the remaining $200 - 5 = 195\mu s$ with subsequent power savings.

It is worth remarking that the idle time is now substantially larger thus allowing greater power savings. However, such a benefit is at the expense of some extra queueing delay suffered by the packets, since these must now wait longer for the beginning of the next cycle time. This effect may degrade the performance of delay-sensitive applications.

C. Delay analysis

Following the previous work by the authors in [1], we can approximate packet delay as:

$$E(D) \approx \frac{3}{2} E(T_{cycle}) \tag{8}$$

which refers to the average amount of time that a packet must wait until its transmission window starts. Hence, the average delay experienced by packets is proportional to the average cycle time.

Therefore, we may adjust the inter-ONU transmission time gap T_{burst} based on a given expected delay objective, D_{target}, such as:

$$\text{Find } T_{burst} \text{ that satisfies: } E(D) = \frac{3}{2} E(T_{cycle}) < D_{target}$$

Example 3 In the 1G-PON of example 2, for a delay target of $D_{target} = 600\mu s$, the value of $E(T_{cycle}) = \frac{2}{3} D_{target} = 400\mu s$, therefore the burst time will be designed as:

$$T_{burst} = (1 - \rho_T) \frac{E(T_{cycle})}{N} = 40\mu s$$

In such a case, the average transmission window is $E(V_i) = \frac{0.2}{1-0.2} T_{burst} = 10\mu s$, and the average idle time per ONU: $E(T_{idle,i}) = 400 - 10 = 390\mu s$ where each ONU may enter the sleep mode.

Finally, as noted in [2], a sleeping ONU can be awaken within $T_w = 125\mu s$. Therefore, the percentage of time that the ONU may spend in the low-poer mode is:

$$\eta_{sleep} = \frac{E(T_{cycle}) - E(V_i) - T_w}{E(T_{cycle})} = 1 - \frac{\rho_T}{N} - \frac{1 - \rho_T}{N} \frac{T_w}{T_{burst}} \tag{9}$$

Finally, the average power consumption is computed as:

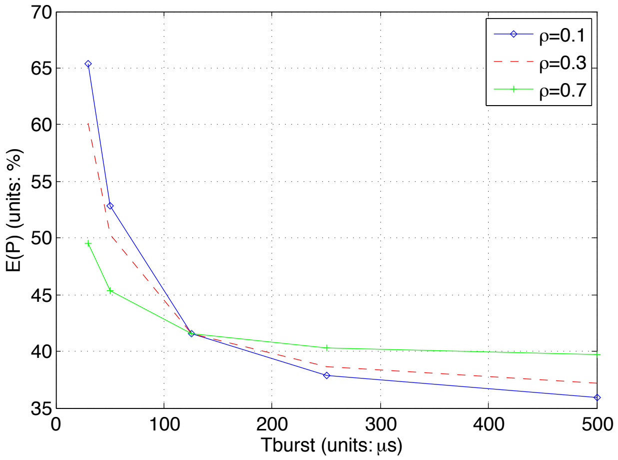
$$E(P) = P_{sleep}\eta_{sleep} + P_{active}(1 - \eta_{sleep}) \tag{10}$$

which weights the portion of time spent in each power mode (active or sleep) times the power consumption in such a mode. The authors in [2] give numbers to the values of $P_{sleep} = 1.28W$ and $P_{active} = 3.85W$.

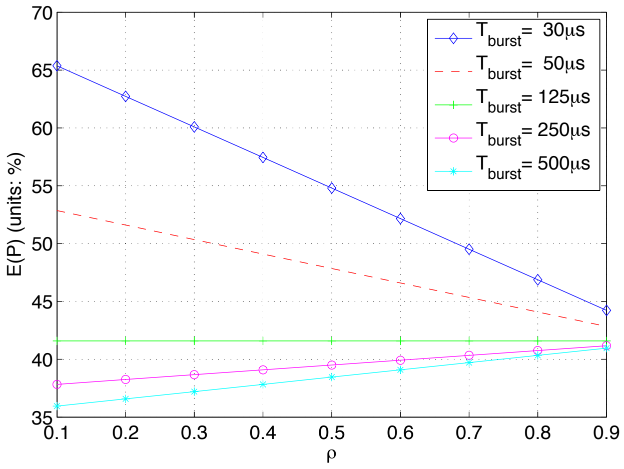
III. NUMERICAL EXAMPLES

Figs. 4(a)-4(c) and 5(a)-5(c) show two numerical examples of the equations above for different values of ρ_T and T_{burst}, for topologies with $N = 8$ and $N = 32$ ONUs respectively. As shown, the achievable power savings are greater for large values of T_{burst}, and especially at low loads.

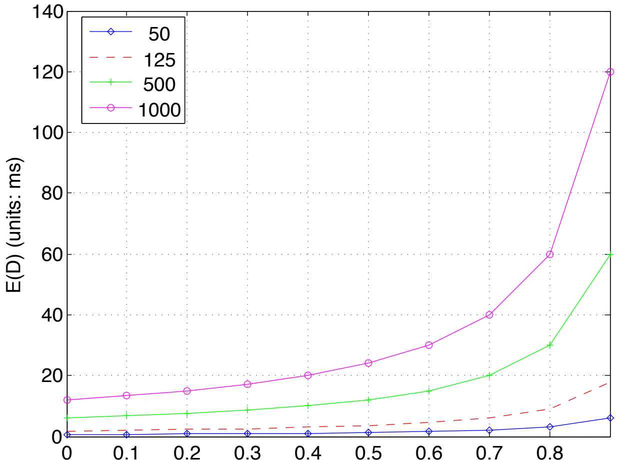
As shown, chosing the appropriate T_{burst} value, power consumption can be reduced to about 40% of the total power in the active mode for $N = 8$ at loads below 0.7, and to 35% for $N = 32$ for the same traffic load range. This comprises substantial energy savings. This comprises about $2.81W$ savings per ONU at a moderate cost in extra delay: $3ms$ for $T_{burst} = 250\mu s$, $N = 8$ ONUs and $\rho_T = 0.1$.



(a) Power consumption

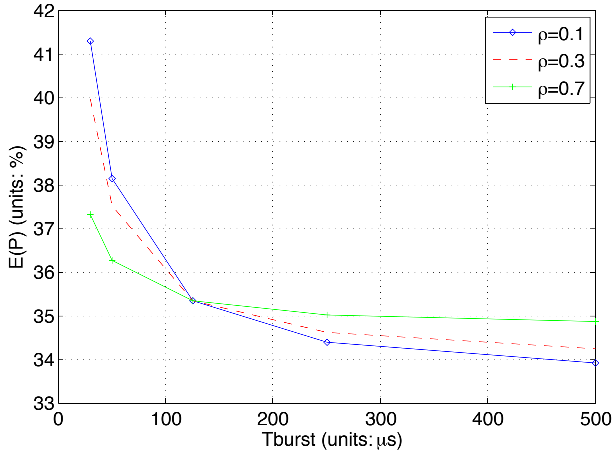


(b) Power consumption

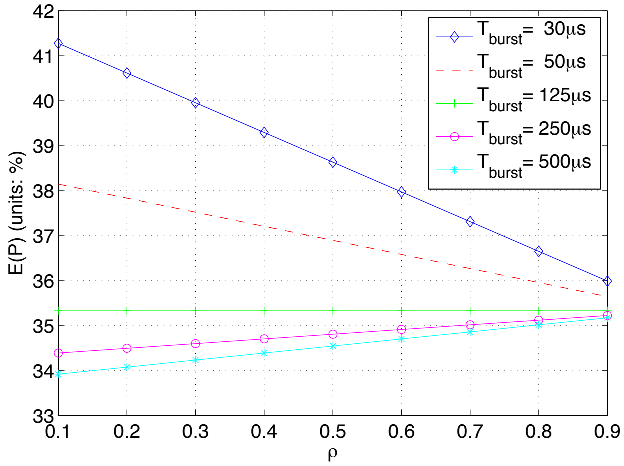


(c) Average delay

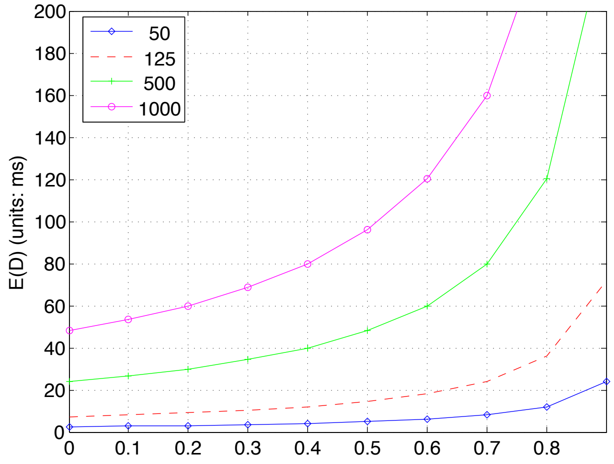
Fig. 4. (a) and (b) Potential power savings, (c) and average delay for $N = 8$



(a) Power consumption



(b) Power consumption



(c) Average delay

Fig. 5. (a) and (b) Potential power savings, (c) and average delay for $N = 32$

IV. SUMMARY AND DISCUSSION

This article proposes a mechanism to increase the energy savings achievable in a TDM PON. Essentially, at low and medium loads, the average cycle time is so small, that it hardly allows the ONUs to go to sleep and wake up on time for the beginning of the next cycle time. However, the average cycle time can be substantially increased by modifying the inter-ONU gap time between the transmission windows of consecutive ONUs. This brings great power savings but may increase substantially the delay experienced by packets, which may impact on the performance of certain real-time applications.

Further work will investigate the trade-off between packet delay and potential energy savings by changing the value of the T_{burst} parameter.

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