# Energy Efficient Dynamic Bandwidth Allocation for Ethernet Passive Optical Networks

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***Abstract*— We propose a dynamic bandwidth allocation (DBA) algorithm for Ethernet passive optical networks (EPON). The DBA algorithm exploits the sleep mode functionality, where the optical network unit (ONU) at the user premises is put to sleep in every cycle according to the traffic load of the ONU. The DBA algorithm achieves up to 93% power savings in comparison to traditional power-ignore DBAs.**

## I. INTRODUCTION

Expected global energy demand is growing faster than 2% per annum [1], and will most likely become unattainable in the years to come. Such a high increase in energy consumption not only poses a serious threat of the scarcity of energy but also increases the consumption of hydrocarbon fuels leading to the emissions of greenhouse gases, which have serious environmental impacts. This has forced the scientific community to solicit the measures of energy efficiency. Among others, one of the factors leading to the upsurge in the energy needs of society is the continuous colossal growth in the information and communication technology (ICT) sector, particularly the Internet. Today, the ICT and the Internet are important constituent factors of power consumption; and they account for approximately 5% and 1% respectively of the total electrical power consumption in developed economies [2]. Recently, there is a paradigm shift in how the Internet is being consumed over years, and because of today's always-online behavior of users and the continual emergence of bandwidth absorbing applications, a substantial increase of electric power of 20 TWh per annum is further required, and this is approximately 8-10% of the total generated power for the ICT [3]. Thus, energy conservation methods will play a key role in shaping up a sustainable society and reducing environmental impacts. The scientific community has realized this, and now green communication is a well-nurtured theme.

Out of the total Internet power consumption, access networks consume about 80 to 90% of the power, and designing energy-efficient access networks can reduce the appalling requirements of energy production and its environmental connotations, and can even lead to significant economic dividends. Passive optical networks (PONs) are presently considered as a promising technology to deliver high data rates to users, and are inherently more energy efficient than their previous counterparts (e.g., ADSL and VDSL) [4]. So far, Ethernet PON (EPON) and gigabit-capable PON (GPON) are the two variants of time-division multiple access (TDMA) PON, which have been used for mass rollout. Presently, an optical network unit (ONU), installed at a customer's premises, accounts for about 60 to 70 % of the energy consumed in current fiber-to-the-home (FTTH) networks. Nevertheless, there have been many efforts to minimize power consumption of the ONUs, and putting ONUs in low power modes is an actively considered solution [5]. In low-power modes, according to the traffic load and or at some specific conditions, the ONU's functionality that is not required is powered down. One of the types of a low-power mode is sleep mode where most of the ONU architecture is powered down when it has no traffic to receive or send [6]-[7]. In this paper, we propose an energy efficient dynamic bandwidth allocation algorithm (DBA) that slots the activity period of every ONU, only during which an ONU needs to wake up to transmit and receive packets.

The remainder of this paper is organized as follows. We discuss the overview and the requirements of sleep mode in EPON in section II. In section III, we introduce the energy efficient DBA algorithm. Section IV gives the simulation results and finally section V concludes the paper.

## II. SLEEP MODE IN EPONs: OVERVIEW AND REQUIREMENTS

We give an overview of sleep modes in EPON and then we discuss the requirements of an energy efficient DBA algorithm.

### A. Overview

EPON is a tree-structured PON technology. In the upstream direction, TDMA techniques are used for scheduling data transmissions from the ONUs at the user's end to the optical line terminal (OLT) to avoid any collisions between the users' data. The ONU sends REPORT messages carrying bandwidth request information based on its queue size, and the OLT sends back a GATE message to the ONU informing the allocated bandwidth. GATE and REPORT messages are 64 byte Ethernet control messages specified in Multi-Point Control Protocol (MPCP). MPCP is specified in IEEE 802.3ah and is used as the signaling protocol in EPON. Furthermore, several DBA algorithms are proposed and Interleaved Polling with Adaptive Cycle Time (*IPACT*) [8] is the most important example of an EPON DBA, in which the polling of each ONU is interleaved, i.e., the next ONU is polled before the transmission from the previous one has arrived at the OLT. In the downstream direction, an OLT broadcasts data to every ONU. Since, the downstream traffic transmission is on the first come first serve basis, the ONU has to remain continuously active to receive the packets.

To minimize the power consumption of the ONUs, several low power modes are actively considered; namely power shedding, doze, deep sleep, and fast (cyclic) sleep [9]. The approaches differ based on the parts of the ONU that are switched off. The power shedding approach shuts down the unused ONU interfaces. In doze state, non-essential functions are powered off with an additional powering off of the ONU transmitter while the receiver remains on. In sleep state, non-essential functional blocks and both the ONU transmitter and receiver are turned off. Deep and fast sleep approaches differ in the periods of sleep, and obviously, the deep sleep approach has comparatively longer periods of sleep. An ONU makes transitions between the various power saving states according to the traffic load of the PON, and a well-suited algorithm is needed to optimize the cyclic transitions between the various states.

In addition to the need of an optimal DBA algorithm, there are also architectural issues with sleep mode. The ONU recovers the clock from the downstream data and remains in synchronization with the OLT. If the receiver of an ONU is powered down, then the ONU loses its synchronization with the OLT. The clock recovery can take about 2-5 ms. After recovering the clock, the ONU also needs to synchronize to the network before being capable of sending upstream traffic. The ONU can synchronize by detecting an Ethernet pre-amble and by subsequently reading the fixed start position delimiter. The synchronization time is equivalent to the inter-arrival time of the Ethernet preamble. The clock recovery and the synchronization time are the overheads associated with switching off the receiver. However, paper [10] shows that the clock recovery time can be reduced to few nanoseconds using a burst mode clock and data recovery (BM-CDR) circuit. The BM-CDR uses a local oscillator, which makes the design more expensive, to maintain synchronization with the OLT clock during sleep mode.

On the other hand, the ONU transmitter is already a BM transmitter, and is thus optimized for a fast turn on/off. To minimize further the transmitter switching time, instead of switching off the whole transmitter block, the authors [11] have proposed the dynamic power save mechanism, where only the laser driver block is switched between active and sleep state in a shorter time. The laser driver block consumes the largest portion of the total current of the transceiver, thus a high power saving efficiency can be achieved even in heavy traffic conditions. Further, there are proposals to use lower power transmitters like vertical cavity surface emitting based lasers (VCSEL) [12]. However, VCSEL based transmitters still have a constraint with the maximum optical power that they can achieve.

### B. Requirements

The energy efficient algorithm must ensure the following requirements:

1) *No degradation of high-priority traffic performance:* The high-priority traffic like voice and interactive video are extremely sensitive to delay and jitter performance, and thus the extra delay induced by the energy-efficient DBA algorithm must be minimal. To meet this end, the polling time of an ONU must be short so that the waiting time of an ONU is minimal and the high priority traffic can be served immediately.
2) *Compatibility with generic and new ONU architectures:* As discussed before, to minimize the degradation of the high-priority traffic, an ONU has to be polled with short time intervals. However, the generic ONU architecture with continuous mode CDR will have large overheads for a short polling time. The generic ONU architectures will be able to support only deep sleep cycles or doze mode. On the other hand, the ONU equipped with BM-CDR can support fast sleep cycles, deep sleep cycles and doze mode.
3) *Minimal negative impacts:* Presently, in the MPCP framework, if an ONU does not reply within 50 ms, the ONU is deregistered. The time to register back an ONU can take as long as 10 seconds or more. Thus, the energy efficient algorithms should assume a maximum sleep period of 50 ms to prevent an ONU from deregistering from the network. Another negative impact of the energy-efficient DBA algorithm is the overheads associated with sleep mode. To minimize the overheads, an ONU should be allocated an activity slot, as large as possible.

## III. ENERGY EFFICIENT DYNAMIC BANDWIDTH ALLOCATION ALGORITHM

First we propose the sleep mode awareness (*SMA*) algorithm and then we discuss the various grant sizing approaches.

### A. Sleep Mode Awareness (*SMA*) algorithm

In the traditional approaches, the downstream traffic is broadcasted to all ONUs and each ONU has to hear continuously the broadcasted traffic. This leaves no opportunity for an ONU to sleep, and it wastes energy, as the ONU has to remain awake at all the time and has to process packets that are not destined for it. We propose a new DBA algorithm, which we refer to as the *SMA* algorithm. In this algorithm, the OLT buffers the downstream traffic for each ONU and only transmits it during a pre-determined activity slot of an ONU. An ONU transmits upstream traffic and receives downstream traffic only during this activity slot. This removes the requirement of an ONU to be awake at all the times and gives an opportunity for an ONU to sleep. It, however, necessitates buffering even in the downstream direction and increases packet delay. *SMA*, like *IPACT*, polls ONUs in a round-robin manner and issues GATE messages to every ONU in each cycle. At the same time, the OLT computes the GATE message as a function of the buffer backlog of the downstream and upstream traffic of an ONU and in addition communicates the next wake-up time to the ONU. The next wake-up time of an ONU is the time of issuing the GATE message of the next cycle for the ONU. Note that the time of issuing the GATE message of the next cycle for an

ONU may not be known at the time of issuing the present GATE message; and thus the OLT has to predict the time epoch of issuing the GATE message of the next cycle. Fig. 1 explains it more clearly. We have assumed two ONUs for clarity. Let us assume that at time T, the OLT knows the buffer statistics of both ONUs and their round-trip time (RTT). Thus, at the transmission time of the first GATE $G_1$ to $ONU_1$, the OLT can easily calculate the grant time of the next GATE message for $ONU_1$. However, at the time of issuing the second GATE message for $ONU_1$, the REPORT message from $ONU_2$ has still not arrived, and thus the OLT cannot calculate the time epoch of the next GATE message for $ONU_1$. In the *SMA* algorithm, the OLT assumes a minimum transmission slot for the ONUs of which the REPORT messages have not arrived at the time of decision. Careful evaluation helps us to know that for an EPON consisting of N ONUs, the time of issuing the $(i+1)^{th}$ GATE message to the $j^{th}$ ONU ($GT_j\,[i+1]$) will depend on the $[i\text{-}1+mod(1,j)]^{th}$ REPORT message of the $[N\text{-}mod((N\text{-}j+1),N)]^{th}$ ONU; where *mod (x,y)* is the remainder of *(x/y)*. For example, the 3$^{rd}$ GATE of the 4$^{th}$ ONU depends on the 2$^{nd}$ REPORT of the 3$^{rd}$ ONU. When the REPORT messages from an ONU arrive, we determine the grant time of the next (in cyclic order) ONU. Using the latest determined grant time of an ONU $k$, we can calculate the minimum time epoch ($MT_p\,[i+1]$) at which the $(i+1)^{th}$ GATE message to the $p^{th}$ ONU is transmitted and is formulated by:

$$MT_p[i+1] = GT_k[i+1] + rtt\,[k] - rtt\,[p] + \Delta \qquad (1)$$

where $rtt[p]$ is the round trip time of the $p^{th}$ ONU and Δ is the minimum transmission slot of the remaining ONUs (the ONUs for which the REPORT has not arrived) as shown in Fig. 2. Note that the actual transmission slot of the remaining ONUs is (Δ+ϒ). From Fig. 2, we can see that the sleep percentage (*SP*) of an ONU is $T_S/T_G$. As the *SMA* algorithm, aligns the reception of the downstream traffic and the transmission of the upstream traffic, the sleep period of an ONU is maximal. Further, note that the GATE MPCP data unit has reserved fields for specific MPCP functions. From these reserved fields, our algorithm uses a 1-byte field to signal the next wake up time to an ONU.

B. Grant Sizing approaches:

There are various approaches by which an OLT can decide the grant for an ONU, referred as grant sizing:

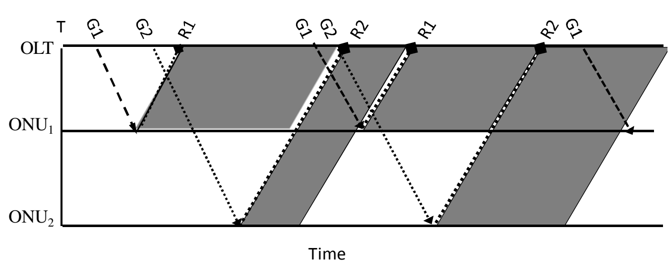


Figure 1: A simple EPON with an OLT and two ONUs showing REPORT (R1 and R2 for ONU1 and 2) and GATE (G1 and G2 for ONU1 and 2) messages transmission.

1) *Upstream Centric (UC):* In this, the activity slot (*AS*) is determined based only on the upstream traffic, as

$$AS = Min\{\frac{T_{cycle}}{N_u}, \frac{B_u}{R_u}\} \qquad (2)$$

where *Min* represents the minimum value of the function, $T_{cycle}$ is the maximum cycle time in which ONUs are polled, $N_u$ is the number of users, $B_u$ is the backlogged upstream bytes for an ONU, and $R_u$ is the upstream data rate.

2) *Upstream and Downstream Centric (UDC):* In this, the *AS* is determined based on both the upstream and the downstream traffic, as

$$AS = Min\{\frac{T_{cycle}}{N_u}, Max\,(\frac{B_u}{R_u}, \frac{B_D}{R_D})\} \qquad (3)$$

where *Max* represents the maximum value of the function, $B_D$ is the backlogged downstream bytes for an ONU, and $R_D$ is the downstream data rate.

3) *Void aware (VA)*: The *UDC* approach chooses the maximum of the upstream and the downstream bandwidth backlog, and hence, it may create voids (cf. Fig. 3), which is the difference between the upstream (US) and the downstream (DS) slot, and deteriorate the performance of the algorithm at a high load. In *VA*, we measure the voids formed and adopt the grant sizing such that the voids does not exceed a definite maximum amount (*MA*). We show

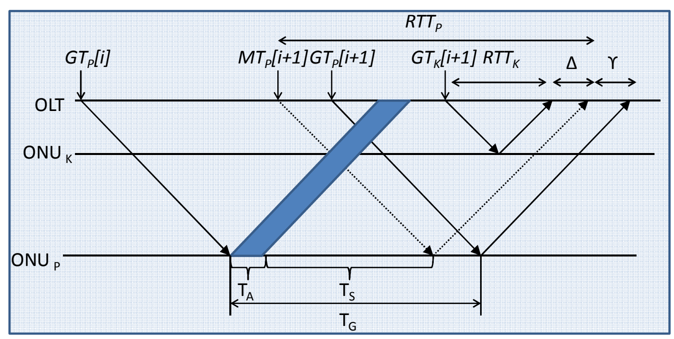


Figure 2: GATE prediction in the SMA algorithm.

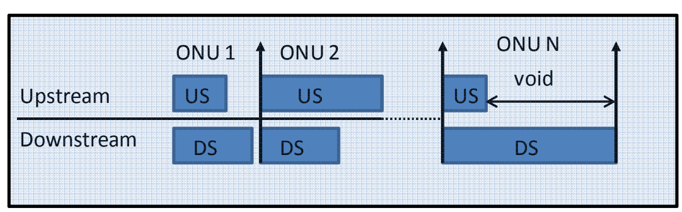


Figure 3: Void formations in *SMA-UDC* approach

$t_u = \frac{B_u}{R_u}$; $t_d = \frac{B_d}{R_d}$;
*IF* $(t_u > t_d)$ *{ If* $(t_u - t_d > MA$, *then* $AS = t_d + MA$; *else* $AS = t_u$ *; }*
*ELSE { If* $(t_d - t_u > MA)$, *then* $AS = t_u + MA$;*else* $AS = t_d$ *;}*

Figure 4: Pseudo-code of *SMA-VA*.

the pseudo-code of the *SMA-VA* approach in Fig. 4, where the voids are restricted to the *MA*.

4) *Minimum Sleep Time (MST): SMA* polls an ONU based on the load. At a low load, the ONU polling time is very short and this requires an ONU to wake up frequently, reducing the time for which an ONU can sleep. In *SMA-MST*, every ONU is granted a minimum *AS* so that the polling time of an ONU is not very short, and even at a very low load; an ONU has a minimum sleeping period. Thus, this approach assures a minimum sleep time for an ONU. First, the *AS* is computed using the *UDC* approach and if the *AS* is smaller than $MST/N_u$, then the *AS* equivalent to $MST/N_u$ is chosen.

## IV. SIMULATION RESULTS

In this section, we study the performance of the proposed DBA approaches by conducting a simulation of an EPON access network with 16 ONUs in the OPNET simulation environment. For our simulation study, we have assumed a maximum ONU load of 100 Mbps, upstream and downstream bandwidth of the EPON as 1 Gbps, maximum OLT to ONU distance of 20 km, maximum cycle time of 5 ms, OLT and ONU buffer of 1 MB, and guard time between adjacent slots as 1 μs. We generated traffic as in [8]. The upstream and downstream load is considered to vary symmetrically. For the *SMA-MST* approach, we have considered a minimum sleep period of an ONU as 1.25 ms. For this analysis, the ONUs equipped with burst mode CDR are assumed and thus the sleep overheads are very little (~ 1 ns) and are ignored.

Fig. 5 gives the upstream packet delay of the various approaches. Since *SMA-UC* gives an activity slot to an ONU keeping in mind only the upstream traffic, the upstream packet delay in the *SMA-UC* algorithm is similar to *IPACT*. However, the *SMA-UC* algorithm will increase the delay of the downstream traffic significantly (cf. Fig. 6) and hence, it will not be useful. The *SMA-UDC* algorithm achieves a compromised delay performance for both the upstream and the downstream traffic. For evaluation of *SMA-VA*, we choose *MA* as 0 and half (0.5) of the maximum cycle time. The *SMA-VA* (0) algorithm increases the packet delay of both the upstream and the downstream traffic significantly at a low load, as the packets of one stream can only be granted if the packets of the other stream are also in the queue. The *SMA-VA* (0.5) algorithm improves the performance at high loads whereas it degrades the performance at low loads. This is because the void formation is only critical at a high load. However, the *SMA-VA* approach does not show much benefit in comparison to the *SMA-UDC* approach. The *SMA-MST* approach maintains the delay bound at a low load and shows similar performance to the *SMA-UDC* approach at a high load. Note that the main advantage of the *SMA-MST* approach is not a lower delay performance but assurance of a minimum sleeping period to an ONU that minimizes adverse affects of frequent mode switching [13].

Fig. 7 shows the performance of various schemes on the sleep efficiency. At a low load, an ONU is polled more frequently, leading to shorter sleeping periods. In addition, the time difference between the predicted GATE and the actual GATE time is more significant over a shorter polling interval, leading to a longer awake percentage of the ONUs at a low load. As the load increases, the ONUs are polled less frequently and thus, they have a longer sleeping period. The *SMA-MST* approach has a high sleep percentage even at a low load because of the longer polling cycles.

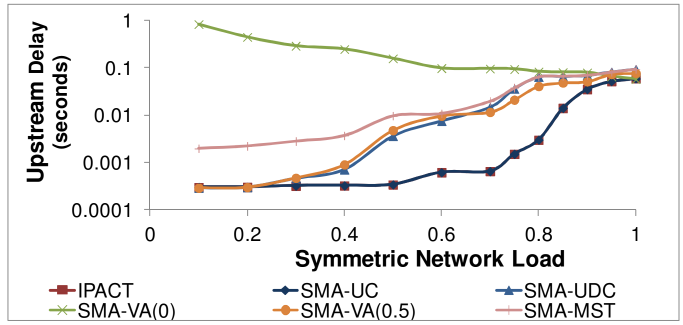

Figure 5: Packet delay of the upstream traffic.

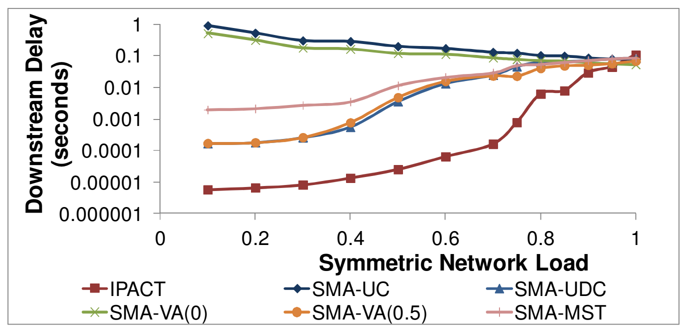

Figure 6: Packet delay of the downstream traffic.

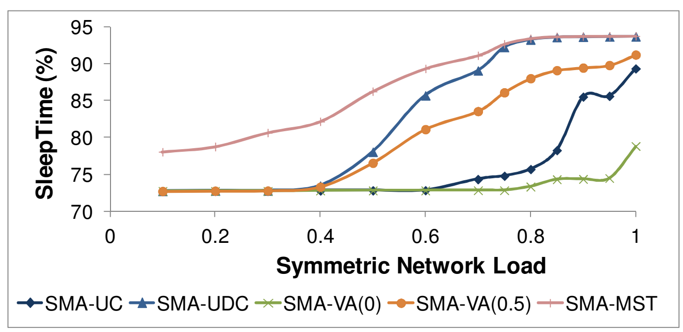

Figure 7: The time (in percentage) in which an ONU remains in sleep state.

## V. CONCLUSIONS

In this paper, we have proposed a sleep mode aware (*SMA*) algorithm. We evaluate the *SMA* algorithm choosing various possibilities of granting an ONU, according to the buffer backlog of the upstream and the downstream traffic. In this context, we proposed four grant sizing schemes, namely upstream centric (*UC*), upstream and downstream centric (*UDC*), void aware (*VA*), and the minimum sleep time (*MST*). The *MST* approach is found to be most useful for maintaining the delay bound and simultaneously reducing frequent mode switching. Besides, in the proposed approaches, an ONU remains in sleep state for about 70 to 93%.

## ACKNOWLEDGMENT

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## REFERENCES

[1] M. Pickavet et al., "Worldwide energy needs for ICT: The rise of power-aware networking," *IEEE ANTS*, New Delhi, India, 2008.

[2] K. Hinton, J. Baliga, M. Feng, R. Ayre, and R. S. Tucker, "Power Consumption and Energy Efficiency in the Internet," *IEEE Network Magazine*, vol. 25, no. 2, 2011, pp. 6 - 12.

[3] White paper available at: http://www.networks-etp.eu/fileadmin/user_upload/Publications/Position_White_Papers/White_Paper_RoF.pdf

[4] J. Baliga, R. Ayre, W. V. Sorin, K. Hinton, and R. S. Tucker, "Energy Consumption in Access Networks," OFC'08.

[5] R. Dhaini, P. H. Ho, and G. Shen, "Toward Green Next-Generation Passive Optical Networks," *IEEE Commun. Mag*., vol. 49, no. 11, 2011, pp. 94 - 101.

[6] A. Dixit et al., "Evaluation of ONU Power Saving Modes in Next Generation Optical Access Networks," ECOC, Amsterdam, Netherlands, Sep. 2012.

[7] A. Dixit, B. Lannoo, D. Colle, M. Pickavet, and P. Demeester, "ONU Power Saving Modes in Next Generation Optical Access Networks: Progress, Efficiency and Challenges," *Optics express,* vol. 20, no. 26, Dec. 2012.

[8] G. Kramer, B. Mukherjee, and G. Pesavento, "IPACT: A Dynamic Protocol for an Ethernet PON (EPON)," *IEEE Commun. Mag*., vol. 40, no. 2, 2002, pp. 74-80.

[9] ITU-T Rec. G.Sup45, GPON Power Conservation, 2009.

[10] S.W. Wong et al., "Sleep Mode for Energy Saving PONs: Advantages and Drawbacks," *IEEE Globecom,* 2009.

[11] E. Igawa, M. Nogami, and J. Nakagawa, "Symmetric 10G-EPON ONU Burst-Mode Transceiver Employing Dynamic Power Save Control Circuit ," OFC'11.

[12] E. Wong, C. A. Chan, P. I. Dias, M. Mueller, and M. C. Amann, "Vertical Cavity Surface Emitting Laser Transmitters for Energy Efficient Broadband Access Networks," ICC'12.

[13] L. Shi, B. Mukherjee, and S. S. Lee, "Efficient PON with Sleep-Mode ONU: Progress, Challenges, and Solutions," *IEEE Network Magazine*, vol. 26, no. 2, 2012, pp. 36-41.