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Adaptive Delay-Aware Energy Efficient TDM-PON

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ABSTRACT

Passive Optical Networks (PONs) are widely adopted as the last-mile technology due to the large bandwidth capacity it provides to end users. In addition, PON is viewed as a green access technology since it reduces energy consumption compared to other access technologies (e.g. Fiber to the Node). However, there is still room for enhancing the energy efficiency of PON further, and we can find many attempts along those lines in academia and industry. A widely used approach to save energy in Time Division Multiplexing (TDM)-PON is to keep the Optical Network Units (ONUs) in sleep mode when they do not have anything to receive or transmit. However, sleep intervals have a direct negative impact on increasing traffic delay. Therefore, energy efficiency in a TDM-PON presents a clear trade-off: the longer an ONU sleeps, the less energy it consumes, but the higher the delay experienced by the downlink traffic, and vice versa. In this paper, we propose an Adaptive Delay-Aware Energy Efficient (ADAEE) TDM-PON solution. The ADAEE aims at saving as much energy as possible while meeting the PON access delay restrictions imposed by the operator. We evaluate our solution in terms of energy consumption and delay performance using real traffic traces. The results demonstrate that the proposed solution can meet delay requirements while being more energy efficient solution compared to the existing solutions.

1. Introduction

There is an urgent need for energy efficient Information Communication Technology (ICT) solutions due to the rise of energy costs. Novel solutions are sought for due to the increasing awareness of the ecological impact of ICT equipment in the environment. For instance, the authors in [1] show that communication networks produced 64 megatons of CO_2 in 2002. Due to the huge demand of Internet services with applications consuming high data rate resources, network capacity has grown very quickly in the past few years. The production of green-house gases by communication networks has expanded very rapidly too. It is interesting to observe that network access equipment is responsible for close to 70% of the overall telecom network energy demand, even though its utilization represents less than 15% [2]. These numbers suggest that research and industry efforts should focus on proposing energy efficient access networks while providing increased access capacity to anticipate future demand.

Time Division Multiplexing (TDM)-Passive Optical Network (PON) (e.g. Ethernet PON (EPON) and Gigabit-capable PON (GPON)) appears to be a promising access technology meeting both requirements: (i) it increases the transmission rate of traditional access technologies up to the order of Gbps and (ii) it consumes much less energy than other access technologies like WiMAX, Point-to-Point Optical Access Network, Fiber-to-the-Node (FTTN) [3].

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Although a TDM-PON is regarded as an energy efficient network compared to other access networks, there is still room for reducing their energy consumption. To improve energy efficiency of TDM-PONs, the effort is concentrated on the Media Access Control (MAC) and the physical layers. In the physical layer, the effort is focused on developing optical transceivers and electronic circuits with lower power consumption and response time. In the MAC layer, most studies propose to apply sleep control and energy-aware scheduling schemes. TDM-PONs can save energy by moving the Optical Network Unit (ONU) to sleep (reducing consumption by turning off power hungry electronic components such as the optical transceiver) when it does not have any incoming or outgoing traffic.

The sleep mode mechanism appears as a good option to save energy since the access traffic is usually bursty [3]. However, the sleep mode approach is challenging in practice because once an ONU is in sleep mode, the Optical Line Terminal (OLT), which is the centralized intelligence in a TDM-PON, cannot communicate with it until that ONU leaves the sleep mode. Therefore, the OLT needs to buffer all the packets while an ONU is in sleep mode. The duration of the sleep interval directly affects the delay experienced by those packets stored in the OLT, since longer sleep interval leads to longer OLT frame storage and thus longer frame delay in the PON-based access network. Therefore, energy saving in PON presents a clear trade-off between energy saving and delay performance.

When an ONU sleeps it loses its connection to the OLT clock and synchronization. After completion of sleep, it takes about 5.125 ms [4] for an ONU to recover its connection to both the OLT clock and synchronization. Therefore, an ONU's sleep interval (usually assigned by the OLT) needs to be long enough for transiting from active mode to sleep mode, then from sleep to active mode, and for recovering connections to the OLT clock and synchronizing with it. Consequently, when the downlink or uplink traffic arrival rate is high and has a strict[1] delay requirement, an ONU cannot move to sleep mode due to the clock recovery and synchronization time [4]. Reducing clock and synchronization time would thus make it possible to efficiently minimize energy consumption in ONUs [4,5].

We found several studies [3,6,7] proposing mechanisms in the MAC layer for managing sleep mode in PON to save energy. In addition, research results have also improved the physical layer of ONUs by defining a new ONU architecture, in particular, for recovering the OLT clock and finishing synchronization quicker, as proposed in [4]. Furthermore, there is ongoing research work on developing optical transceivers and circuitry with low power consumption and low response time [5].

In fact, the actual role of an ONU should be to reduce energy consumption as much as possible while always meeting the access delay requirements imposed by the operator. All previous studies have focused on one or the other of these aspects, but none have dealt with both issues at the same time. In this paper, we propose Adaptive Delay-Aware Energy Efficient (ADAEE) solution that aims to: (i) meet access delay requirements and, (ii) at the same time reduce the energy consumption as much as possible. ADAEE presents two main contributions: (i) a novel ONU architecture and (ii) a novel algorithm to compute the maximum (T_{max}) and minimum (T_{min}) sleep interval values. Both contributions together allow fulfilling operator delay requirements while maximizing energy savings.

We use 24 h traces of real time traffic to evaluate the ADAEE proposal and compare it with two previously proposed solutions. We also evaluate performance of the ADAEE using Constant Bit Rate (CBR) and Variable Bit Rate (VBR) traffic. The results demonstrate that in different scenarios (strict delay and relaxed delay) ADAEE solution is the most energy efficient solution compared to the existing ones while it meets the access delay requirement. Therefore, to the best of our knowledge, the ADAEE is the first proposal that addresses energy efficiency linked to the obligation of fulfilling the required delay for the PON traffic. In addition, we examine how sleep mode affects TCP throughput. The results exhibit that in compare to existing ones (proposals that consider sleep mode to improve energy efficiency of PON) ADAEE shows a best throughput performance.

The remainder of this paper is structured as follows: Section 2 introduces the TDM-PON background and related work. Section 3 describes our proposal, the ADAEE approach, in detail. We present the performance evaluation of our proposal in Section 4 together with a comparison to two earlier proposals from the literature. Finally, Section 5 provides conclusions.

2. Related work

In this section we first briefly describe operation of a TDM-PON, and then we present those related works that influence our proposal classified into two categories: MAC layer and physical layer approaches.

2.1. TDM-PON background

A TDM-PON utilizes a broadcast-and-select mechanism for downlink transmission (from OLT to ONU). In a TDM-PON, downlink frames are transmitted through a fiber and then broadcasted using a passive component called splitter. Usually the splitting ratio is *1:n*, where *n* can be 16, 32, 64 or 128 ONUs. Fig. 1 depicts a generic TDM-PON architecture. In order to identify the destination ONU, the OLT uses a unique identifier for each of them (i.e. 'Alloc ID' in GPON [8] and unique Logical Link Identifier (LLID) in EPON [9]). Furthermore, ONUs do not know when the downlink traffic arrives at the OLT and the time when the OLT schedules the traffic transmission for them. Therefore, IEEE standard 802.3ah [9] specifies that ONUs should keep its optical receiver continuously on in order to capture all downlink frames and check whether they are destined for it or not. Clearly this solution is far from being energy efficient since there are many periods of time in which an ONU does not have any incoming traffic, and thus

[1] In all this paper we use the term strict delay requirement to refer those cases in which the delay in the access network needs to be very low (e.g. 4 ms), while we use the term relaxed delay requirement for longer PON access delay (e.g. 30 ms)).