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Building an Energy-efficient Uplink and Downlink Delay Aware TDM-PON System

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ABSTRACT

With the increasing concern over the energy expenditure due to rapid ICT expansion and growth of Internet traffic volume, there is a growing trend towards developing energy-efficient ICT solutions. Passive Optical Network (PON), which is regarded as a key enabler to facilitate high speed broadband connection to individual subscribers, is considered as one of the energy-efficient access network technologies. However, an immense amount of research effort can be noticed in academia and industries to make PON more energy-efficient. In this paper, we aim at improving energy saving performance of Time Division Multiplexing (TDM)-PON, which is the most widely deployed PON technology throughout the world. A commonly used approach to make TDM-PON energy-efficient is to use sleep mode in Optical Network Units (ONUs), which are the customer premises equipment of a TDM-PON system. However, there is a strong trade-off relationship between traffic delay performance of an ONU and its energy saving (the longer the sleep interval length of an ONU, the lower its energy consumption, but the higher the traffic delay, and vice versa). In this paper, we propose an Energy-efficient Uplink and Downlink Delay Aware (EUDDA) scheme for TDM-PON system. The prime object of EUDDA is to meet both downlink and uplink traffic delay requirement while maximizing energy saving performance of ONUs as much as possible. In EUDDA, traffic delay requirement is given more priority over energy saving. Even so, it still can improve energy saving of ONUs noticeably. We evaluate performance of EUDDA in front of two existing solutions in terms of traffic delay, jitter, and ONU energy consumption. The performance results show that EUDDA significantly outperforms the other existing solutions.

1. Introduction

Recent studies (e.g. [1,2]) reveal that there is a stupendous growth of CO_2 footprint due to rapid expansion of ICT. It is worth noticing that currently ICT is responsible for consuming 8% of total electricity consumption in the world [3]. This has triggered many research initiatives which have led to develop energy-efficient protocols and hardware development in order to minimize energy consumption of network equipment. Researchers from both industries and academia have centered their efforts on maximizing energy-efficiency of core and access network equipment. Recently, one of the most interesting findings associated with network utilization is presented in [2]. Authors in [2] impart that around 70% of overall Internet energy consumption is consumed by access network equipment. However, utilization of these equipment is only around 15% [4,5]. Consequently, in recent years, there has been an increasing interest in developing energy-efficient protocol and hardware design for access network equipment.

To date, there are several access network technologies, such as Passive Optical Networks (PON), Worldwide Interoperability for Microwave Access (WiMAX), Wireless Fidelity (WiFi) and Digital Subscriber Line (DSL). Among these access network technologies, PON is considered as a very promising technology. This is because PON provides not only huge data rate (up to the order of Gbps) but also it consumes significantly less energy compared to other technologies like WiMAX [6,7]. Among different PON architectures, such as Wavelength-Division Multiplexing-PON (WDM-PON), Time Division Multiplexing-PON (TDM-PON) and Hybrid WDM/TDM-PON, TDM-PON has been widely deployed in many countries (e.g. China, Korea, and Taiwan).

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A generic TDM-PON (e.g. Ethernet PON (EPON) and Gigabit-capable PON (GPON)) is composed of an Optical Line Terminal (OLT) (centralized intelligence of a TDM-PON), a passive splitter and several Optical Network Units (ONUs), which are installed at user premises, as depicted in Fig. 1. The splitting ratio of a passive splitter in a TDM-PON is termed as *1:n*, where *n* can be 16, 32, 64 or 128 ONUs. A TDM-PON architecture employs a single wavelength in the downlink direction (OLT to the ONUs), whereas a separate wavelength is deployed for uplink communication (ONUs to the OLT). In a TDM-PON, downlink is broadcast-and-select mechanism. The OLT marks the downlink traffic with a unique identifier, so that each of the ONUs can identify its corresponding traffic (e.g. in EPON, an OLT uses a unique Logical Link Identifier (LLID) [8]). On the other hand, the OLT controls the uplink transmission of all connected ONUs by assigning grant time in time domain for each ONU to send its uplink traffic. In this manner, a TDM-PON can secure that an uplink traffic conflict will not occur. Thereby, an ONU sends bandwidth request message to inform the OLT its uplink bandwidth requirement. The OLT collects all bandwidth requests from its connected ONUs and uses Dynamic Bandwidth Allocation (DBA) algorithm to measure upstream transmission slots for each of the ONUs. After calculating transmission slots, the OLT notifies the ONUs.

Although PON is more energy-efficient compared to other access technologies, there is a big room to improve its energy saving performance while meeting Quality of Service (QoS) of its traffic [6,7]. Findings in [9] reveal that ONUs are responsible for 65% power consumption of a PON system. The earlier standards (e.g. IEEE 802.3ah [8]) consider that ONUs should be kept always on. It is because in the downlink direction of a TDM-PON is true broadcast. An ONU never knows when the OLT will have traffic to send. Consequently, an ONU needs to be always on to receive downlink traffic, thus wasting energy unnecessarily. Researchers have pointed out this limitation of the earlier TDM-PON standards and they have come up with sleep mode mechanism and low-power-consuming optical transceivers for ONUs in order to reduce energy consumption.

One of the widely applied approaches used for ONUs of TDM-PONs to improve energy saving performance is sleep mode in which an ONU switches off its power hungry components during a defined amount of time [10,7]. Although sleep mode is an efficient approach to design an energy-efficient TDM-PON, it could affect traffic delay performance significantly if sleep interval lengths of ONUs are not carefully decided. In fact, an ONU's sleep interval length brings a trade off relationship: the longer the sleep interval length of an ONU, the less energy it consumes, but the higher the traffic delay, and vice versa [7]. Therefore, to date, many researchers have centered their efforts in developing sleep mode deciding algorithms (e.g. [6,7,11–14]). Energy saving in TDM-PONs has gained attention of different standardization bodies. For example, ITU-T G.sup 45 [15] has introduced four different power saving techniques for an ONU: power shedding, doze mode, deep sleep mode and fast sleep (these four power saving techniques are briefly explained in Section 2).

When an ONU in a TDM-PON uses sleep mode to improve its energy saving performance, generally, the OLT is in charge of deciding sleep interval lengths of the ONU. An ONU supporting sleep mode can have several states (e.g. *Sleep state*, *Active state*). The OLT calculates a sleep interval length of an ONU using a sleep interval length deciding algorithm and notifies the ONU in absence of traffic [7,11,13,14]. The ONU leaves *Sleep state* after the assigned sleep interval period expiration and waits for the OLT's further instruction. The OLT invokes the ONU to stay active if there is any frame to receive and/or transmit. Otherwise, the OLT instructs the ONU to move into *Sleep state* mentioning next sleep interval length. It needs to mention here that whenever an ONU moves into *Sleep state* it loses OLT's clock and synchronization [10]. Therefore, after completion of *Sleep state*, to establish communication with the OLT, the ONU needs to spend around 2 ms to gain OLT's clock and synchronization [11,13,14]. In this paper, the time required for gaining OLT's clock and synchronization is referred as transition time. The power consumption of an ONU during the transition time is almost the same as in the *Active state* [16].

Most of the sleep mode deciding algorithms (e.g. [5,7,12–14]) take into consideration only the presence or absence of downlink traffic while deciding sleep interval lengths for ONUs. In those solutions, authors consider that a sleeping ONU should leave *Sleep state* whenever it is interrupted due to uplink traffic arrival. Similarly, energy-efficiency aware TDM-PON standards (e.g. Service Interoperability in Ethernet Passive Optical Networks (SIEPON) IEEE 1904.1 [17] and ITU-T G.988 [18]) recommend that an ONU's *Sleep state* should be interrupted on arrival of uplink traffic (sleeping ONU should leave *Sleep state* upon arrival of uplink traffic). Leaving *Sleep state* before the allocated sleep interval period due to uplink traffic arrival is referred to as early wake-up in [15,17,18]. The most important limitation of the solutions that consider ONU early wake-up lies in the fact that, during high uplink traffic arrival scenario, an ONU will not be able to complete the OLT's assigned sleep interval length, and thus an ONU will end up spending significant amount of energy for *Sleep state* to *Active state* transition. To solve this problem, some researchers suggest in their solutions that uplink and downlink traffic forwarding should take place at the same time (e.g. [19,20]). However, these solutions suffer from one or more major drawbacks that we explain in Section 2.

Fig. 2 provides an explanation to understand the downside of early wake-up. Based on aforementioned discussion, this figure compares two cases: (i) an ONU uses early wake-up and leaves

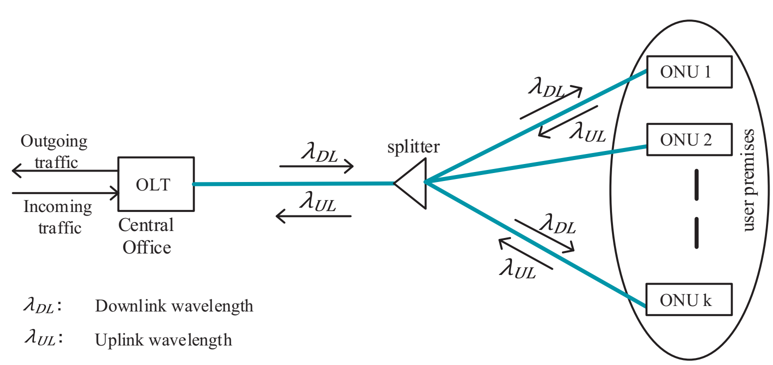

Fig. 1. Generic TDM-PON architecture.