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Energy-saving scheme based on downstream packet scheduling in ethernet passive optical networks

Lincong Zhang, Yejun Liu *, Lei Guo, Xiaoxue Gong

College of Information Science and Engineering, Northeastern University, Shenyang 110819, PR China

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ABSTRACT

With increasing network sizes, the energy consumption of Passive Optical Networks (PONs) has grown significantly. Therefore, it is important to design effective energy-saving schemes in PONs. Generally, energy-saving schemes have focused on sleeping the low-loaded Optical Network Units (ONUs), which tends to bring large packet delays. Further, the traditional ONU sleep modes are not capable of sleeping the transmitter and receiver independently, though they are not required to transmit or receive packets. Clearly, this approach contributes to wasted energy. Thus, in this paper, we propose an Energy-Saving scheme that is based on downstream Packet Scheduling (ESPS) in Ethernet PON (EPON). First, we design both an algorithm and a rule for downstream packet scheduling at the inter- and intra-ONU levels, respectively, to reduce the downstream packet delay. After that, we propose a hybrid sleep mode that contains not only ONU deep sleep mode but also independent sleep modes for the transmitter and the receiver. This ensures that the energy consumed by the ONUs is minimal. To realize the hybrid sleep mode, a modified GATE control message is designed that involves 10 time points for sleep processes. In ESPS, the 10 time points are calculated according to the allocated bandwidths in both the upstream and the downstream. The simulation results show that ESPS outperforms traditional Upstream Centric Scheduling (UCS) scheme in terms of energy consumption and the average delay for both real-time and non-real-time packets downstream. The simulation results also show that the average energy consumption of each ONU in larger-sized networks is less than that in smaller-sized networks; hence, our ESPS is better suited for larger-sized networks.

1. Introduction

Recently, developing "green networks" has been a critical focus, as energy saving in networks has faced unprecedented challenges [1–3]. In particular, the "last mile" broadband access network has received significant attention because energy consumption in these networks accounts for approximately 75% of the entire network [4]. As a predominant modern broadband access technology, the Passive Optical Network (PON) has become the most feasible and energy-efficient solution. Due to the use of optical fibers closer to the end users in addition to the passive nature of the remote nodes, PON consumes the smallest energy among the various access technologies, which include Wireless Fidelity (WiFi) [5,6], Worldwide Interoperability for Microwave Access (WiMax) [7], Fiber-To-The-x (FTTx) [8], and Digital Subscriber Line (xDSL) [9]. Nevertheless, the energy consumption of PONs can be further reduced because the devices are not in use at all times.

In this paper, we focus on Ethernet PON (EPON), which has been widely deployed in recent years. The devices used in the typical Time Division Multiplex (TDM) EPON include an Optical Line Terminal (OLT), a splitter and several Optical Network Units (ONUs), which are constructed in a tree topology. In the upstream direction, the traffic from the end users is first aggregated at the ONUs and is then sent to the OLT. All ONUs share the upstream channel to the OLT in a time division manner. Conversely, in the downstream direction, the OLT broadcasts the downstream traffic to all ONUs. The ONUs only reserve the traffic designated for themselves and discard the rest.

In EPON, the energy is mainly consumed by the OLT and ONUs, where the power consumption of an OLT is 20 times of an ONU [10]. Nevertheless, as the highest aggregate node, the OLT can rarely be turned off because it connects the PON with the Internet. As a result, current efforts to reduce the energy consumption in EPON have primarily focused on ONUs. Several energy-saving measures are currently used for ONUs in EPON.

First, the power consumption of the ONUs can be reduced in light of the hardware structure. Ref. [11] developed low-power ONUs with integration technology, which decreased the power consumption of the investigated ONUs from 10 W to 6 W.

* Corresponding author. Address: College of Information Science and Engineering, Northeastern University, P.O. Box 365, Shenyang 110819, PR China. Fax: +86 24 83684219.

E-mail address: haveball@yeah.net (Y. Liu).

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Second, the ONUs can be allowed to sleep when the traffic is low. In reality, devices in access networks, such as ONUs, tend to be underused by approximately 15% [12]. Because the traffic occurs suddenly and dynamically, the ONUs do not keep busy all of the time. Consequently, the ONUs can go into sleep modes under low or zero traffic conditions. Refs. [13,14] proposed algorithms for ONU sleep when the traffic load is lower than the low-level threshold, at which point another sleeping ONU will be woken up when the network traffic load is higher than the high-level threshold. In this case, the traffic designated to the sleeping ONU is rerouted to other active ONUs.

Third, energy-efficient protocols can be designed in EPON. This method designates the sleep start time and wakeup time for ONUs. Refs. [15,16] proposed two ONU sleep schemes, named Upstream Centric Scheduling (UCS) and Downstream Centric Scheduling (DCS), which are based on the use of a Multipoint Control Protocol (MPCP) in EPON. In UCS, the downstream traffic load only can be transmitted during the upstream transmission slot. If the downstream traffic is significantly more than the upstream traffic, a large delay is caused for the downstream traffic due to queuing. In DCS, if any traffic exists either upstream or downstream, the ONU should not go to sleep. Therefore, DCS reduces the downstream traffic delay while consuming more energy than UCS.

In fact, 60–70% of the ONU power consumption is due to the transceiver and back-end circuit [11]. Hence, allowing the transmitter and receiver to sleep is another possible approach for ONU energy-saving management. Ref. [17] proposed four power levels for ONUs, achieved through the use of different transmitter and receiver states. Two sleep mode scenarios for ONUs are proposed, including multiple Dynamic Bandwidth Allocation (DBA) cycles and one DBA cycle. In the multiple DBA cycles scenario, the transmitter and receiver are allowed to sleep for more than one cycle only if the sleep duration is no more than the maximum tolerated time. In the one cycle scenario, the transmitter goes to sleep after completing the transmission, and it is woken up via the ONU MAC protocol. However, sleeping the receiver is significantly more complicated because the receiver does not know the condition of the downstream traffic. Hence, the transmission interval of an ONU in the downstream is designed to be determined by the sum of the downstream traffic of all other ONUs. Then, the receiver can sleep for a period based on a function of the interval time.

Energy-saving problems also have been studied in various PONs. Refs. [18–20] noted that a 10G-EPON consumes more energy than a 1G-EPON due to the significantly higher line rate. Based on this idea, they developed a single-threshold policy [18,19] and a dual-threshold policy to prevent frequent switching of the link rates [20]. In addition to adding the adaptive link rate, the cyclic sleep mode is also used as one of the energy-saving modes that are specified in the ITU-T Recommendation G. sup45, while the other is doze mode [21]. Further, ITU-T G.984 for Gigabit PON (GPON) specifies the ONU sleep modes for four types, including the ONU power shedding mode, the ONU dozing mode, the ONU fast/cyclic sleep mode and the ONU deep sleep mode [22]. In the first mode, beyond the optical link, some functions and services can be turned off. The power consumption in this mode is the highest among the four modes. In the ONU dozing mode, the transmitter can be turned off without the presence of upstream data. This mode consumes the second highest power after the ONU power shedding mode. The ONU fast/cyclic sleep is defined by allowing the ONUs to stay in a sequence of sleep cycles. Its power consumption is less than that of the ONU dozing mode. The ONU deep sleep mode consumes the least power because both the transmitter and the receiver can be turned off. Meanwhile, the network performances are also most seriously degraded in this mode. Recently, a method for combining the four modes has appeared. An ONU deep sleep mode combined with a dozing mode was proposed to achieve the maximum possible energy saving in Ref. [23].

Although Refs. [13–16,18–23] studied various energy-saving methods, they did not focus on energy consumption in the independent components of the ONUs. In Ref. [17], although the energy consumption of the transmitter and receiver was considered, the performances including the packet delay were not addressed. Therefore, an energy-saving scheme that considers both the components of the ONU and the packet delay remains a challenge, and this challenge has motivated our work.

In this paper, we consider the energy-saving components of the ONUs, which include the transmitter, the receiver and the ONU in its entirety. We first propose an algorithm and a rule for downstream packet scheduling under inter- and intra-ONU conditions to ensure that the real-time packet that arrives earliest also can be sent first and that all real-time packets can be sent before the non-real-time packets. Then, we develop a hybrid sleep mode for ONUs that considers the combination of ONU deep sleep and independent sleep for transmitters and receivers. To realize this combination, a modified GATE control message is designed with 10 time points for the sleep processes of the transmitter, the receiver and the entire ONU. Based on the packet scheduling algorithm and rule in addition to the hybrid sleep mode, we propose an ONU sleep scheme named the Energy-Saving scheme based on downstream Packet Scheduling (ESPS), which minimizes the energy consumption of ONUs and reduces the packet delay as much as possible.

To the best of our knowledge, the work in this paper is the first study to combine the independent sleep mode for transmitters and receivers with the ONU deep sleep mode, and this work also is the first study to design the ONU sleep scheme by scheduling both inter- and intra-ONUs. The rest of the paper is organized as follows: Section 2 gives the problem statement; Section 3 presents the scheduling of downstream packets; Section 4 proposes the hybrid sleep mode; Section 5 describes the proposed ESPS scheme in detail; Section 6 details the simulation and its analysis; and Section 7 concludes this paper.

2. Problem statement

2.1. Assumptions and notations

In the ONU deep sleep mode, both the transmitter and receiver are turned off, while the other components (e.g., the digital circuitry) remain active at all times. Therefore, the power of the ONU in a deep sleep state is produced by the always-active components. When the transmitter/receiver remains active, the always-active components are also working. We assume there are K ONUs in a given EPON, and enable *tx* and *rx* to denote the transmitter and the receiver of *ONU*, respectively. We let *acc* denote the always-active components. Because the energy-saving components that we consider in this paper include *tx*, *rx* and *acc*, we give the relative parameters for those components in the following list.

- i: The index of the ONU, $1 \leqslant i \leqslant K$.
- N: The maximum polling cycle that OLT polling ONUs in the simulation time.
- n: The index of the polling cycle, $1 \leqslant n \leqslant N$.
- E_{wakeup}: The energy consumption of the wakeup process for an ONU.
- P_{tx}, P_{rx}: The power consumed by the transmitter and the receiver while active, respectively.
- P_{sleep}: The power consumed when an ONU is in a state of deep sleep.
- $T^{n}_{tx,i}$: The active duration of the transmitter of an ONU_i in the nth cycle, $1 \leqslant i \leqslant K$.

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