Optical Fiber Technology 36 (2017) 271–280

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Regular Articles

Delay-aware adaptive sleep mechanism for green wireless-optical broadband access networks

Ruyan Wang [a], Alei Liang [a], Dapeng Wu [a,*], Dalei Wu [b]

[a] School of Communication and Information Engineering, Chongqing Univ. of Posts and Telecommun., Key Laboratory of Optical Communication and Networks, CQ, 400065, China
[b] Department of Computer Science and Engineering, University of Tennessee at Chattanooga, TN 37403, USA

ARTICLE INFO

Article history:
Received 27 December 2016
Revised 23 April 2017
Accepted 2 May 2017
Available online 10 May 2017

Keywords:
Wireless-optical broadband access network (WOBAN)
Quality of service (QoS)
Energy efficiency
Passive optical network

ABSTRACT

Wireless-Optical Broadband Access Network (WOBAN) is capacity-high, reliable, flexible, and ubiquitous, as it takes full advantage of the merits from both optical communication and wireless communication technologies. Similar to other access networks, the high energy consumption poses a great challenge for building up WOBANs. To shot this problem, we can make some load-light Optical Network Units (ONUs) sleep to reduce the energy consumption. Such operation, however, causes the increased packet delay. Jointly considering the energy consumption and transmission delay, we propose a delay-aware adaptive sleep mechanism. Specifically, we develop a new analytical method to evaluate the transmission delay and queuing delay over the optical part, instead of adopting M/M/1 queuing model. Meanwhile, we also analyze the access delay and queuing delay of the wireless part. Based on such developed delay models, we mathematically derive ONU's optimal sleep time. In addition, we provide numerous simulation results to show the effectiveness of the proposed mechanism.

1. Introduction

In recent years, the explosive growth of high-bandwidth applications is challenging the service capability of existing broadband access networks [1]. A passive optical network (PON) has been widely considered to be a perfect solution to offer high bandwidth and excellent stability. However, PON cannot provide users with anytime-anywhere access services due to its high deployment cost [2,3]. On the other hand, wireless access networks are flexible and low-cost [4,5], but they can only offer very limited bandwidth [6]. In order to combine the merits from the both types of access networks, researchers have proposed a new network architecture, i.e., hybrid wireless-optical broadband access network (WOBAN) [7]. This type of access network can provide customers with high-capacity, reliable, flexible, and ubiquitous services.

Energy consumption of the Information and Communication Technology (ICT) sector has become a severe issue. It has been reported that ICT has accounted for 8% of the global energy consumption, and its energy consumption is still increasing dramatically in the future. More importantly, access networks contribute to 70% energy consumption of ICT [8,9]. This problem is much more severe in WOBAN because it comprises myriads of access devices that are constantly switched on and off. Some existing studies have shown that the major source of energy consumption is the optical network units (ONUs) in WOBAN [10]. To reduce ONUs' energy consumption, some researchers have proposed a sleep method, with which an ONU is scheduled to be in a sleep state. This method can reduce the energy consumption by 80% around [11,12].

The longer is the sleep time, the lower is the energy consumption [12]. However, making ONUs sleep can cause high packet delay. A newly arrived packet has to be buffered in an optical line terminal (OLT) when the ONU is in a sleep state. In this case, the packet delay over WOBANs will be prolonged, which inevitably affects the QoS experienced by customers.

To address this problem, in this work a delay-aware adaptive sleep (DAS) mechanism is proposed to reduce energy consumption while still guaranteeing the QoS in WOBAN. Specifically, a new analytical model is developed to evaluate the packet delay over the optical part. Meanwhile, an analytical model is derived to analyze the packet delay over a wireless mesh network. Then, the ONU's optimal sleep time is obtained based on both delay models. In particular, the total delay has to meet the QoS constraint of given services.

The main contributions can be summarized as follows:

First, two analytical delay models are developed for the optical and wireless parts, respectively.

---

* Corresponding author.
E-mail address: wudapengphd@gmail.com (D. Wu).

http://dx.doi.org/10.1016/j.yofte.2017.05.003
1068-5200/© 2017 Elsevier Inc. All rights reserved.

Second, a delay-aware adaptive sleep mechanism that can guarantee the given QoS level is designed. Particularly, the ONU's optimal sleep time is derived.

The rest of this paper is organized as follows. In Section 2, the related works are briefly presented. Section 3 describes the considered network model. Section 4 details the two analytical delay models for both optical and wireless parts, respectively. Section 5 describes an adaptive sleep mechanism. The performance of our proposed mechanism is evaluated in Section 6, and Section 7 concludes this paper.

2. Related works

The key issue of energy saving is to design reasonable sleep time for ONUs. Currently, researchers have proposed several solutions to determine the sleep time for fast sleep mode. Those solutions can be divided into two categories: Fixed Sleep Time (FST) algorithms [13–17] and Variable Sleep Time (VST) algorithms [18–20]. In the FST algorithm, the sleep time is a fixed value. Whenever there are no packets to be sent to ONU, the OLT sends a fixed sleep time to the ONU. Then, the ONU switches to sleep state and wakes up after the sleep timer expires. Contrarily, the widely used VST algorithm is Exponential Sleep Time (EST) algorithm, where the sleep time of an ONU starts from a pre-defined minimum time and exponentially increases up to the maximum time as long as there is no downstream and upstream traffic for that ONU. After the sleep timer expires, the sleep time of that ONU restarts from the minimum length after the transmission of packets.

Togashi et al. proved that excessively long ONU sleep time not only causes long latency but also results in more energy consumption. Then, they derived the optimal sleep time to minimize energy consumption [13]. Ref. [14] introduced a probing-based cyclic sleep mode mechanism based on the FST algorithm. The analysis provides explicit mathematical expressions for the energy consumption and packet response delay in the ONU. Bang et al. established an analytic model to evaluate performances such as energy consumption and delay based on buffer sizes, sleep periods, and arrival rates [15]. Kubo et al. proposed a hybrid power-saving mechanism, which combines the fast sleep mode with adaptive link rate control mechanism. The ONU's state switches according to the presence or absence of packets. Meanwhile, the downstream transmission rate is adjusted according to the number of packets in the OLT [16]. Newaz et al. introduced an analytical model to evaluate the energy consumption in four kinds of ONU power levels and applied this model to the FST algorithm. Results proved the accuracy of the analytical model [17]. Zhang and Ansari studied the transitions between ONU's states from the perspective of the control and scheduling of MAC layer. Besides, energy efficiency is achieved by making the length of the sleep time changes exponentially [18]. Newaz et al. firstly proposed a novel structure of ONU, which is capable of selecting an appropriate sleep mode to achieve the maximum energy saving. Then, OLT and ONUs calculate the exponentially changing sleep time according to the downstream traffic simultaneously [19]. Ren et al. found that a shorter minimum sleep time leads to the higher energy consumption and less delay, whereas a longer maximum sleep time results in the lower energy consumption and higher delay. The authors also claimed that it is important to obtain the suitable minimum sleep time and maximum sleep time in the EST algorithm [20].

As can be seen, the above mechanisms cannot meet the dynamical features of network traffic and only pay fewer attentions to adjusting ONU's sleep time according to the QoS requirements of packets. In addition, the delay of wireless domain varies greatly and has a great effect on the value of the sleep time. Therefore, the energy efficiencies of these above mechanisms can be further improved by considering the delay of wireless domain when deriving the optimal sleep time for ONU.

3. Network model

Fig. 1 shows the considered WOBAN architecture with the Ethernet passive optical network (EPON) and wireless mesh network (WMN) parts. In the EPON, the OLT, placed in the Central Office (CO), is connected to a splitter through the optical fiber [21]. Moreover, the splitter is connected to several ONUs that are connected to the WMN by wireless gateways. Wireless routers communicate with these gateways. A user end (UE) accesses the WOBAN by connecting to a wireless router nearby. For downstream traffic, the OLT broadcasts packets from the Internet to all ONUs. Then, the ONU determines to forward the packets to their destination via one or multiple wireless links according to the logical link identifications. The transmission process of upstream traffic is the inverse of that of downstream traffic.

4. Delay evaluation

The process of the fast sleep mode is shown in Fig. 2, where an ONU alternately switches between the sleep and active states, and the OLT controls the sleep time. Specifically, after a sleep period ends, the ONU sends a wake-up message (Confirmation) to the OLT. Once no incoming packets are stored in the OLT, the OLT will send a Sleep Request (SR) message with sleep time T_{sl} to the ONU; otherwise, the OLT will send an SR message with sleep time 0 to keep the ONU continuously receiving packets. If there are no further packets to transmit, the OLT will send the ONU another SR with a pre-configured sleep time to turn off the transmitter and receiver. Since the SR messages are only sent upon receiving the Confirmation message, the newly arrived packets at OLT during the ONU sleep state will be buffered [22]. How often the OLT would send the SR to the ONUs depends on ONUs' sleep interval. If the sleep interval is long, the time interval between two SRs is long too.

By considering the above process, the expected buffering time of a packet in an OLT can be obtained as

$$d_{OLT} = \frac{T_{sl}^{i} + T_{ov}}{2} \tag{1}$$

where T_{ov} is the synchronization overhead time for each ONU wakeup; and T_{sl}^{i} is the sleep time of ONU i.

Packets requested by a UE are sent to and then buffered in the OLT from the Internet, until the ONU wakes up and receives packets. Then, the ONU sends the packets to the UE via a wireless gateway and the corresponding wireless path. The propagation delay between the OLT and ONU is negligible because the packets are transmitted over fiber. Thus, the average total transmission delay of a downstream packet consists of the delay between the

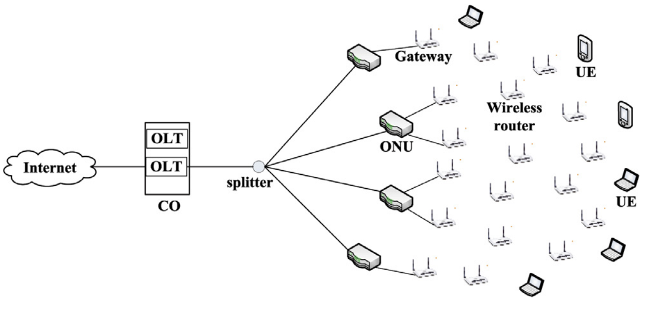

Fig. 1. The considered architecture of WOBAN.