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Performance analysis of passive optical networks with energy saving through the integrated sleep mode ☆

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ABSTRACT

Improving the energy efficiency has become an important aspect of designing optical access networks to minimize their carbon footprints. In this context, interleaved polling with adaptive cycle time (IPACT) with the integrated sleep mode is considered as a medium access control (MAC) scheme to improve the energy efficiency of passive optical networks (PONs). The decision criterion for energy saving is to put an ONU in the sleep mode when no upstream and downstream traffic exists, without impairing the desired quality of service (QoS) requirements in terms of the mean packet delays. We derive approximated and conservative closed form expressions of the upstream and downstream mean packet delays for the integrated sleep mode by modeling a PON as an N-user M/G/1 queue with reservations and vacations. Simulation experiments are conducted to validate the need of joint consideration of upstream and downstream traffic to avoid excessive delays in packet transmissions. Simulation experiments also validate the analytical results and show that the mean packet delays are relatively insensitive to packet arrival statistics for large sleep periods. Hence, our analytical results may also be applied to more practical scenarios with non-Poisson packet arrivals.

1. Introduction

The Internet and its associated telecommunication devices are playing an important role in our daily lives. However, the rapidly increasing energy consumption of communication infrastructures is causing a lot of environmental concern. According to numerous research studies, improving the energy efficiency of data communication network has been extensively recognized as a significant issue for the future [1–4]. It has been observed that, in current telecommunication networks, most energy is consumed in broadband access networks; research studies like [2,4–6] reveal that broadband access networks consume about 70 percent of the total energy consumption of all telecommunications network equipments.

In particular, [4] reveals that more than 60 percent of the total energy in access networks is dissipated by consumer modems. This implies that the energy consumption of optical access networks can considerably be reduced by applying the sleep mode in the customer premises network equipment [3]. Owing to the swift growth of access network connectivity and high bandwidth demands for modern applications, energy consumption of future broadband access networks would continue to rise [4,7]. Therefore, within both the academia and industry, several researchers focus on designing energy efficient mechanisms for data communication networks.

A passive optical network (PON) has emerged as an attractive and promising technology to provide low-cost point-to-multipoint fiber access to local subscribers [8]. In particular, a PON is a point-to-multipoint optical network, where an optical line terminal (OLT) resides at the central

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office (CO) and is connected to multiple optical network units (ONUs) many ONUs at remote nodes through one or multiple passive optical splitters [8,9].

A PON provides incorporated infrastructure capable of carrying multiple services such as data, voice, and video, and also provides basic optical fiber infrastructure without having external power supply outside CO, thus considerably reducing the operational cost [8]. In contrast to conventional access techniques, numerous advantages of using PONs include relatively high bandwidth, long distance coverage, low cost, and transparent upgrade capability [8–10].

In the upstream direction, the OLT allocates to ONUs the fiber capacity by means of an upstream bandwidth arbitration method to avoid packet collisions. The interleaved polling with adaptive cycle time (IPACT) is typically used for this purpose [9,11,12]. In [13], the author analyze both the gated service and the limited service, but under the assumption of a fixed packet size. The author in [14] show that a PON can be analyzed using an M/G/1 queueing model as long as the propagation delays between the OLT and ONUs are relatively small, which is typically the case for access networks.

For the downstream direction, the OLT broadcasts to all ONUs data packets, which each ONU filters and accepts only those that are destined to itself [10]. However, ONUs have to continually listen and inspect downstream traffic, and hence remain active even when there is no traffic, causing a significant waste of energy [7]. The key sources of energy wastage in a PON comprise eavesdropping, idle listening, and control packet overhead. An extensive review on energy consumption in optical access networks, i.e. PONs, can be found in [5]. Approaches to reduce the energy consumption in optical access networks include the sleep mode, adaptive link rate (ALR), and hybrid mechanisms [15].

The basic purpose of employing the sleep mode is to reduce the energy consumption by switching off the unused functions on various components in the absence of traffic on the link [7,15]. However, some issues like synchronization of ONUs have to be addressed prior to implementation of the sleep mode [16].

ALR is proposed to decrease the energy consumption of an Ethernet link by means of changing the data rate with respect to link utilization [15,17]. The hybrid mechanism includes both a cyclic sleep function with a variable sleep period that enables appropriate adjustment of the sleep period according to traffic conditions, and an ALR function with a dual-threshold policy that prevents frequent switching of link rates [15].

Among the mentioned approaches for reducing energy consumption, putting some network devices into the sleep mode is widely adopted [2,15,16,18,19]. A large number of research studies carried out within academia and industry led to proposals of employing the low power or sleep mode for elements of PONs, in particular at the ONUs [2,5,19,20]. The idea of implementing the sleep mode to ONUs is indeed compatible with the broadcast and time division multiple access (TDMA) nature of PONs [20].

While there have been several research investigations on how to operate the sleep mode in a PON, most results rely on computer simulations to study the effects of device sleeping [2,3,15,16,19]. These results demonstrate that sleeping can significantly reduce the energy consumption. In [19], different types of sleep modes corresponding to different power levels for ONUs are proposed and investigated. Though, the impact of the proposed scheme to the desired QoS requirement in terms of the mean packet delay is not articulated.

However, for practical operations, more specific guidelines on how to select the sleep period subject to the QoS constraints such as the maximum mean packet delay are being investigated in [1]. Our previous work in [1] does not take into account downstream traffic, which is indeed the majority of traffic. Hence, if ONUs sleep both the transmitter (for upstream) and the receiver (for downstream), buffer overflows can occur at the OLT and lead to packet losses. Therefore we propose what is referred to as integrated sleep mode in this paper to take into account downstream traffic in addition to upstream traffic.

Very few analytical works exists for the performance of PONs with the sleep mode, in this regards, [18] provides a careful analysis on how to select the sleep period based on the packet delay constraint. However, upstream traffic is considered using offline scheduling in which the OLT waits to receive the queue lengths from all the ONUs before making the scheduling decision in each cycle. This mechanism can incur a lot of idle time between successive cycles.

There is a lack of an analytical model which can offer mathematical basis for the quantification of various system parameters for the implementation of energy efficient PONs for upstream and downstream direction simultaneously, while satisfying the QoS constraints.

The main contributions of this paper are the following.

1. In this research, we present an integrated approach for the sleep mode activation to be used for PONs. The goal is to improve the energy efficiency without violating the QoS requirement in terms of the mean packet delay constraints for both upstream and downstream transmissions. For energy saving, the sleep mode of each ONU is activated considering packet queue lengths for both upstream and downstream traffic simultaneously. An ONU turns off both optical transmitter and receiver during the allocated sleep period.
   We attempt to keep the protocol as close as possible to the original IPACT for the analytical results to be relevant to practical systems. We analyze the mean packet delay for a PON with integrated sleep mode by modeling the system as an M/G/1 queue with reservations and vacations.
   The proposed integrated sleep mode can help avoid excessive packet delays due to sleeping and requires minor modification of the prevailing IPACT protocol. The modified IPACT with the integrated sleep mode, referred to as Green-IPACT, is compared with the baseline case of IPACT with the sleep mode based on upstream traffic only.
2. The analysis of the mean packet delay in a PON operating IPACT with integrated sleep mode is carried out. The analytical results are then used to guide the selection