Towards an Effective Energy Efficient Passive Optical Network

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Abstract—**Communication networks' energy consumption poses a considerable threat to the environment stability. The expansion of access networks, which constitute the main playground of the Internet backhaul, is accompanied by numerous energy inefficient devices and equipments. Passive optical networks (PONs) is a potential dominant technology on the field of access networking, hence the reduction of the consumed energy of the optical devices forms a critical issue. In this paper, an efficient green PON is introduced, having two main targets: a) to reduce the energy consumption, by allowing optical devices to operate longer in sleep mode, and b) to maintain PON's good performance. Beyond the green provisioning, the proposed scheme is able to increase occasionally the network performance in terms of mean packet delay and packet drop ratio. This is accomplished by reducing the amount of control messages between subscribers, operating in sleep mode, and central office, allowing more bandwidth to be allocated for data delivering.**

Keywords-bandwidth allocation; energy consumption; passive optical network

I. INTRODUCTION

The vast growth of Internet and web-based services leads to various benefits and opportunities, while giving rise to potential threats. In order to support the ever-increasing number of subscribers, handle excessive traffic demand and satisfy user requirements, preferences and constraints, operators deploy new network elements and hardware components, leading, thus, to increased amounts of energy for their constituent operation. This way, a serious threat is posed to the environment that should be carefully addressed.

Considering that Internet equipment consumes roughly 8% of the total energy in the United States, while it is expected to grow by 50% within a decade [1], in addition to the fact that renewable energy sources are still immature to replace the current 'dirty' energy production, green networking technologies operating based on environment-friendly rules, inducing reduced or eliminated human impact on nature, are gaining momentum. Improved electronic and photonic devices, low-energy switching techniques, and new energy efficient architectures and protocols may contribute towards this direction.

Access networks constitute a major energy consumer. It is estimated that access networks are responsible for the 70% of the overall telecommunication networks energy consumption [2]. This may be attributed to the fact that access networks involve a huge number of active communication devices. Hence, access network constitutes the major energy consumer. In this perspective, building a green Internet necessitated for low energy access networks, incorporating efficient power management schemes.

Passive optical network (PON) is one of the most promising candidates to govern broadband access, due to its essentially unlimited and cost-effective bandwidth potential. FTTx (Fiber To The x) technologies are realized by PONs, creating optical light-paths without including optical-to-electrical conversion. Even though PONs include passive equipment, energy consumption reduction still constitutes a major challenge.

Inefficient network design induces significant waste of electricity [3]. Additionally, idle or under-utilized network components consume energy without operating efficiently [4]. Given that access networking equipments are less than 15% utilized [5], a major portion of energy savings could be achieved by reducing the consumption of idle and/or under-utilized network equipment.

In this work a novel energy efficient scheme is proposed in order to reduce the energy consumption in PONs. The main idea is to deliberately control the optical components' operational mode based on communication requirements. A well known algorithm is adopted, known as slow start [6], which puts active optical components to sleep mode. Concurrently, unnecessary control messages are blocked and the gained bandwidth is re-allocated to the actual data transfer. The results seem promising, since the proposed effective green PON performs well, significantly reducing the energy consumption.

The remainder of this paper is organized as follows. In Section II, related efforts on energy management are provided. Section III gives the background of the PON technology.

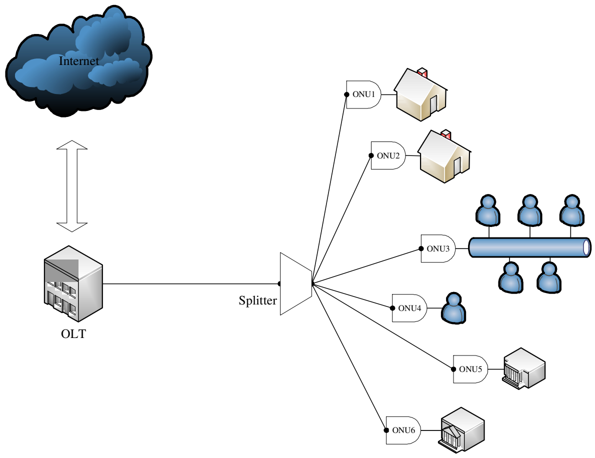

Figure 1. A typical PON architecture with an OLT and 6 ONUs, each located at different position

Section IV describes the proposed novel energy efficient scheme, while Section V presents simulation results and provides numerical examples. Finally, Section IV concludes this paper.

II. RELATED WORK

Nowadays, power management constitutes an issue of paramount importance. In this perspective, wireless networking has attracted the attention of the researchers, with emphasis laid on the design and implementation of energy efficient strategies and protocols for wireless ad hoc and sensor networks [7, 8]. Many related efforts focus on developing real-time power aware routing protocols, adopting dynamic modification of the transmission power. Some works propose energy-aware routing solutions, without, however, over shadowing other performance factors. Additionally, network coding techniques are examined, so as to reduce the time of information exchange.

Efficient energy management in the context of access networks is not studied to the same extent. Recent notable contributions [2, 9] provide comparisons between different types of access networks. Focusing on optical networks, 10GEPON (10 Gigabit Ethernet Passive Optical Network) Task Force Recommendations [10, 11], attribute high significance to energy consumption in PONs, proposing low power state for PON equipments, shedding power and speed shedding in user network interface and access network interface, etc, Even though, at system level, low power devices and energy efficient chips development has been an active area of research [12], energy efficient network design and energy-aware coordination schemes in optical networks are still in their infancy.

The literature include some initial contributions on energy efficient PONs. In [13] an adjustable-timer-based multi-point handshaking protocol is proposed to set ONUs in sleep mode in purpose. Authors in [14] suggest two energy efficient mechanisms for 10G-EPON. The former one determines whether an ONU should be set in sleep mode according to current traffic conditions. The latter one, manages the line rate that connects the OLT and ONU, allowing its diminution in lower rates in order to reduce the power consumption. In [15] possible implementations of sleep mode are presented along with two novel ONU architectures that reduce the clock recovery overhead. The authors claim that the proposed architectures may offer considerable energy savings that can reach 50% of the overall energy consumption. Efforts in [16] present the design of an 'elastic OLT' in sense of power saving, whereby the available power budget is fully utilized by extending the transmission distance and multiplying the splitting ratio. Authors of [17] pose a different approach on energy efficiency issue by introducing traffic engineering as potential solution. They devise an efficient power-aware scheme for optical backbones, whereby the operational power is minimized. For this purpose, a power-aware routing technique is suggested, which 'puts the traffic where the bandwidth is'. Simulation results indicate that this technique may achieve noticeable power savings. Based on our current findings in the literature, the efforts on energy efficiency on PONs are insufficient, keeping the problem open and challenging. In this work, a novel power-saving approach is proposed to cover the needs in an offline EPON, whereby the transmission coordination is concentrated but may lead to energy efficient actions and procedures.

III. PASSIVE OPTICAL NETWORKS

Typically, a PON consists of an Optical Line Terminal (OLT) located at the central office (CO) and multiple Optical Network Units (ONUs), which are scattered around a certain region. The OLT constitutes the PON's gateway, while the ONUs provide direct connection to the subscribers. In order to avoid costly numerous point-to-point direct connections, PON utilizes a passive optical splitter, which receives a single optical fiber from an OLT and distributes the incoming signal to multiple single optical fibers. Each fiber is connected to a single ONU, creating a point-to-multipoint architecture, providing an all-optical path without involving any kind of conversion. The most attractive topology is the tree topology, depicted in Figure 1.

Subscribers' communication with the CO is realized in two directions. In downstream direction, the OLT broadcasts all signals to all ONUs, while the ONUs select and process the data rows that are destined to them. Upstream direction is used by ONUs in order to send data to OLT. Since multiple ONUs share a common transmission medium in the upstream direction, coordination is necessitated in order to guarantee collision free communication. Specifically, the OLT governs ONUs' transmissions following a common transmission schedule. Two kind of channels (distinct wavelengths) are utilized: the control and the data channels. Control channels are used for carrying control information, e.g., the transmission grant from OLT to a specific ONU, including information about the transmission channel (if there more than one available) and the exact time of the transmission. Data channels are the main transmission routes, carrying the data streams for each direction.

A well known coordination protocol is the MultiPoint Control Protocol (MPCP) [18]. Beyond the discovery and registration procedures, MPCP involves two important control messages: the GATE message and the REPORT message. During steady state operation, the OLT controls the ONUs' transmission window with GATE messages. The REPORT messages inform the OLT about the queue status of the connected ONUs. In other words, REPORT messages carry the bandwidth demand of ONUs based on the subscribers' traffic requests. GATE messages are carried via the control channel(s), while REPORT messages are piggybacked into the real data and both are transmitted via the available data channels. It is important to note that if an ONU has nothing to send (i.e., its queue is empty) a REPORT message of 64 bytes (equal to the minimum Ethernet frame) is sent to inform the OLT about its idleness.

PONs may involve online or offline transmission scheduling. In an online scheduler a given ONU is scheduled for upstream transmission as soon as the OLT receives the REPORT message from the ONU. Regarding the selected channel for transmission, the OLT schedules the upstream transmission for an ONU on the data channel available earliest among all data channels supported by the ONU. Online scheduling constitutes a fast and direct way of coordinating the upcoming transmission demands but it operates without global knowledge of the current bandwidth requirements of the other ONUs. This fact limits the efficiency of online scheduling and reduces somehow its potential for energy efficient coordination.

On the contrary, offline scheduling or interleaved polling with stop, as it is also known, forces the OLT to wait for all ONU REPORT messages before proceeding to the schedule construction. This affords the OLT the opportunity to provide fair bandwidth distribution, effective scheduling, and a potential energy-aware coordination. For all those reasons, offline scheduling is adopted in this work to provide energy-efficient bandwidth distribution. For more information about MPCP and PONs' coordination can be found in [19]. A recent paradigm of offline scheduling can be found in [20].

IV. Energy Efficient Scheme

In this Section, the aim and the motivation of this work are presented along with the introduced energy efficient scheme.

A. *Scope and Motivation*

The proposed energy efficient scheme aims at providing an effective green PON without over shadowing its performance. This could be achieved by putting deliberately a portion of the active optical equipment to sleep state. However, deep sleep, as the transmitter and receiver sleep is called, makes the ONU totally blind, since the ONU is unaware of the incoming traffic (i.e., downstream direction). Because of this, the deep sleep technique is abstained in order to avoid QoS deterioration. Consequently, this work focuses on transmitter sleep that is applied when no upstream traffic is observed.

As previously mentioned, PONs are composed by one passive element (splitter), which operates without power, and two types of active components, the ONUs and the OLT. For the OLT it is crucial to continuously operate normally, since it controls the whole network. On the other hand, a single ONU manages only a group of subscribers and in some case only a single subscriber. In the light of the aforementioned aspects, it is interesting to examine the case where a set of totally idle ONUs could be set to sleep mode of operation, under specific traffic conditions.

Even though current IEEE 802.3ah/802.3av standards do not specify low-power state for ONU devices [21], recommendations have been given by IEEE 802.3av Task Force in order to include low-power state for ONUs. An active ONU are approximately consumes 10 W [22], while it is estimated that during sleep mode the energy consumption could be reduced by 90% [10]. Additionally, existing commercially available ONUs include TX_DISABLE state, which disables the transceiver [22]. These observations indicate that a sophisticated energy management scheme could be effective, putting deliberately idle ONUs to sleep mode.

B. *Energy Management Algorithm*

The proposed energy efficient scheme was inspired by the well known slow start algorithm, the congestion control mechanism adopted by TCP (Transmission Control Protocol) protocol. TCP utilizes a critical variable, called congestion window, which specifies the amount of data the sender is allowed to transmit to the receiver. This window increases (exponentially and/or linearly) if the transmitted data are acknowledged by the receiver and it is reduced if a timeout occurs. A timeout indicates a possible congestion state and sets the congestion window to its initial value, while the aforementioned process is repeated.

A similar algorithm is proposed in this work to determine whether an ONU can be set to sleep mode (i.e., transmitter sleep mode). The main decision criterion adopted is the traffic profile of ONUs. Similarly to congestion window, we define the sleep window, which reflects the cycles that an ONU can be put to sleep state. Each ONU maintains its sleep window, while its traffic profile is obtained from the REPORT message. An ONU having empty buffer sends a typical empty REPORT message to inform the OLT that has no data to send. In this case, the ONU's sleep window is increased, while the ONU is set to sleep for the cycles indicated by the sleep window. During this period, the OLT does not poll the specific ONU. For each cycle that the ONU stays in sleep mode, the sleep window is reduced by one. The OLT polls the specific ONU, when the sleep window reaches its initial value (i.e., the unity), If the REPORT message remains empty then the sleep window is doubled and the ONU is set to sleep state, otherwise the algorithm sets the ONU to active state and the sleep window is set equal to its initial value (unity). Along with the sleep window, a threshold is used to determine the frequency of the consecutive idle intervals. The adopted sleep threshold takes an initial value for each ONU. If the sleep window overcomes the value of sleep threshold, then the sleep window grows linearly, by adding one for each polling attempt with empty REPORT. When an ONU exits the sleep period, its sleep threshold is set to one half of the current sleep window.

TABLE I. MAIN SIMULATION PARAMETERS

Round Trip Time (RTT)	**Uniformly distributed [100 μsec- 200 μsec]**
Transmission rate	**1 Gbps (per channel)**
Generated Traffic	**Pareto with 40 sources a = 1.6 for ON state a = 1.3 for OFF state**
Buffer size	**100 Kb**
GRANT window	**10 Kb**
GUARD_TIME	**5 μsec**
GRANT policy	**Limited sizing**
REPORT message	**64B**
Sleep threshold	**16 (cycles)**
Simulation Time	**3 sec**

Algorithm 1 Energy Management Scheme

```
Set the array of sleep window ( sw ) equal to unity
Initialize the array of sleep threshold ( st )
FOR each cycle
   IF ONU is active THEN
      OLT polls ONU
      IF ONU returns empty REPORT THEN
         ONU is set to sleep state
         IF ONU's sw is larger than its st THEN
            sw = sw + 1
         ELSE
            sw = 2 * sw
         END_IF
      ELSE
         st = sw / 2
         sw = 1
      END_IF
   ELSE
      sw = sw - 1
      IF sw = 1 THEN
         ONU is set to active state
      END_IF
   END_IF
END_FOR
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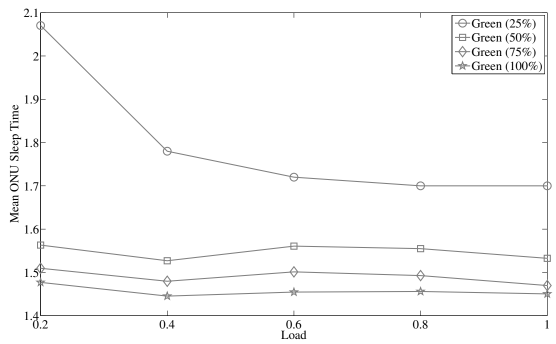

Figure 2. Mean ONU sleep time of the PON (single data channel).

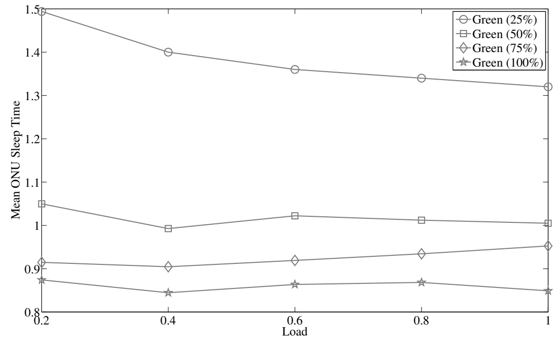

Figure 3. Mean ONU sleep time of the PON (two data channels).

Finally, the algorithm defines that the duration of sleep mode cannot overpass 5 seconds, in order to avoid mis-performance. Algorithm 1 describes the aforementioned logic

V. PERFORMANCE EVALUATION AND RESULTS

In this Section, we provide experimental results indicative of the performance of the proposed scheme. The novel energy efficient strategy is evaluated in EPON considering offline scheduling and its performance is compared to the pure offline scheduler as it has been presented in Section III [23]. The adopted PON architecture consists of 16 ONUs and an OLT. The ONUs have been randomly placed so as to provide a realistic scenario. Hence, different round trip times (RTTs) are assumed, which are randomly generated based on a uniform distribution U[100 μsec, 200μsec] and correspond to 20 - 30 Km distances between the OLT and the ONUs.

The optical fiber that connects OLT and ONUs may be a single channel or a multiple channel fiber. In the former case, the single channel fiber supports 1 Gbps, while in the latter case each channel can transmit at a 1 Gbps rate, resulting in a cumulative 2 Gbps transmission rate. The receiving traffic of each ONU, i.e., the produced upload traffic by subscribers, is generated based on self similarity property. More specifically, an aggregation of 40 sources, each consisting of alternating Pareto-distributed ON/OFF periods, is used, having shape parameter a = 1.6 for ON and a = 1.3 for OFF periods.

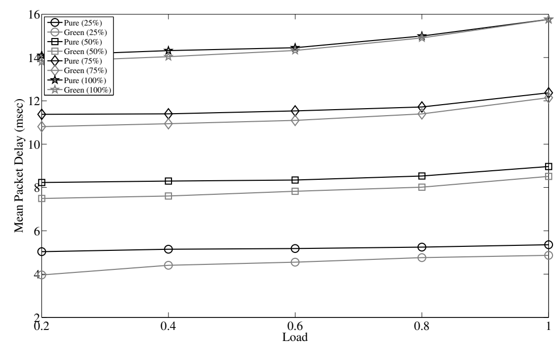

Figure 4. Mean packet delay of the PON (single data channel).

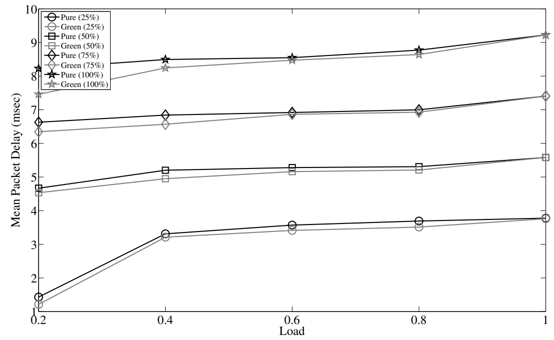

Figure 5. Mean packet delay of the PON (two data channels).

ONUs are equipped with a buffer, temporary storing the generated traffic. It is assumed that the buffer consumes negligible energy. Each buffer is able to store 100 Kb per ONU. Regarding the GRANT window, the limited GRANT-sizing technique is adopted [23], which is quite helpful, since it prevents any ONU from monopolizing the shared bandwidth. According to this technique, the GRANT size is set to the reported buffer size up to a maximum GRANT window. For the following experiments, this window is equal to 10 Kb. Finally, it is worth mentioning that the GUARD_TIME (a small time gap between allocations for protection reasons) is set to 5 μsec. Table I summarizes the main simulation parameters.

All experiments have been conducted for three secs of simulation time. Four realistic scenarios are examined, where 25%, 50%, 75%, and 100% of the connected ONUs are assumed to be active (they receive traffic). The rest of them are considered as temporarily idle. The performance of the proposed green PON is illustrated by grey curves, while the performance of the pure offline framework, called as pure, is depicted by black curves.

Fig. 2 and Fig. 3 depict the mean ONU sleep time, that is the mean duration of each period the ONU is set to sleep state, measured in msec. In Fig. 2, a single channel fiber is used, while in Fig. 3 two data channels are utilized. It is evident that larger number of idle ONUs leads to longer sleep periods, since the proposed energy management mechanism, detecting their empty REPORT messages, keeps them in sleep mode.

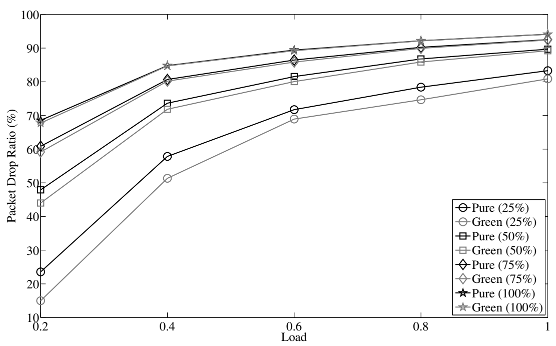

Figure 6. Packet drop ratio (single channel).

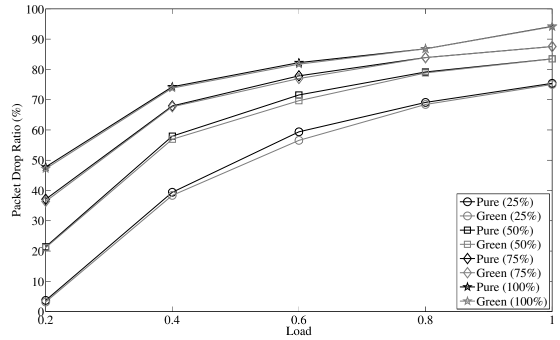

Figure 7. Packet drop ratio (two data channels).

The impact of the proposed scheme to the performance of PON is examined in Figs 4 and 5. As a first step, the performance metric considered is the end-to-end mean packet delay. In Fig. 4, the considered PON utilizes a single channel, while the PON in Fig. 5 incorporates two data channels. From the obtained results, it may be concluded that the introduced scheme not only avoids to over shadow the network performance, but it succeeds in reducing slightly the delay. This may be attributed to the fact that the bandwidth associated with control messages destined to and/or originated from ONUs (i.e., REPORT messages) in sleep state are re-allocated to serve data requests of other active ONUs. Of course, these findings are evident under the assumption that the transition from normal to sleep state and vice versa holds without extra delays.

Following, we consider the packet drop ratio performance metric. Figs. 6 and 7 provide indicative results of the superiority of the proposed green mechanism. Clearly, the energy efficient scheme allows more data to be delivered to the OLT, as a major portion of unnecessary empty REPORT messages has been eliminated. In this manner, the otherwise wasted portion of bandwidth is distributed to the real needs of active ONUs.

As a final note, our obtained results indicate that energy efficiency can be effectively realized, without negatively impacting network performance. On the contrary, sleep state mechanisms can affect positively the operation of a synchronous PON, reducing its energy-aware impact to the environment as well as to our society.

VI. CONCLUSIONS

This paper falls within the area of efficient power management in access networks. Specifically, an effective energy efficient scheme for passive optical networks is proposed. The introduced efficient green PON determines the traffic conditions of optical network units and sets the idle devices in (transmission) sleep mode. Concurrently, needless control messages are obviated, allowing, thus, more available bandwidth for allocating real data. The proposed scheme is able to reduce the energy consumed in the optical backhaul. It is a common thought that green networking could be a serious stronghold against the energy demanding

Internet growth; hence our research will focus on energy consumption issues, designing and implementing adaptive energy efficient strategies.

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