An Adaptive Power Management Scheme for Ethernet Passive Optical Networks

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***Abstract*—Undoubtedly, energy consumption in communication networks poses a significant threat to the environmental stability. Access networks contribute to this consumption by being composed of numerous energy inefficient devices and network equipment. Passive Optical Networks (PONs), one of the most promising candidates in the field of access networking, should avoid this bottleneck in the backhaul power consumption by lowering the energy use of the optical devices. In this paper, we move towards that direction by introducing an energy efficient power management scheme that encompasses two major goals: a) to reduce the energy consumption by allowing the optical devices to enter the sleep mode longer, and b) to concurrently maintain the network performance. To this end, we focus on the energy consumed by the optical network units (ONUs). The intelligence of the ONUs is stimulated by enhancing the decision making in determining the duration of the sleep period with learning from experience mechanism. Learning automata (LAs) are charged to address this challenge. The evaluation of the proposed enhanced power management scheme reveals considerable improvements in terms of energy savings, while at the same time the network performance remains in high levels.**

***Index Terms*—bandwidth allocation; energy efficiency; learning automata; passive optical networks**

I. Introduction

The Internet growth underpins a vast array of benefits, opportunities, and services. However, the last decade, a considerable threat looms; the growing energy consumption caused by Internet-related networking equipment. Unfortunately, the current communication technologies demand more amount of energy to support the ever-increasing number of subscribers as well as the additional power demanding equipment. The energy consumption of these technologies appears to be a daunting challenge. It is estimated that the access network is responsible for the 70% of the overall energy consumption of the communication network [1]. Furthermore, an access network comprises of a perpetually growing number of active devices, a fact suggesting that the energy consumption will continue to rise during the next decades [1]. Hence, the access network constitutes the major energy consumer.

Passive Optical Networks (PONs) represent one of the most promising candidates to dictate broadband access due to their essentially unlimited bandwidth potential [2]. Even though PONs include passive equipment, which operate without power, the energy consumption issue still holds. Idle or under-utilized network components consume energy without operating efficiently [3]. It is obvious that a major portion of energy savings could be achieved by scaling down the consumption of these idle or under-utilized networking equipment.

The present work proposes an energy efficient power management scheme that reduces the energy consumption of the Optical Network Units (ONUs) operation in Ethernet PONs (E-PONs) and ten-gigabit Ethernet PONs (10G-EPONs). The innovation lies in the enhancement of the ONUs regarding the determination of the sleep time period when a sleep session is initialized. Many bandwidth allocation schemes assume a fixed and predefined sleep period, since the traffic conditions remain unknown and often unpredictable. However, a sleep period having predefined length could either limit the energy savings or even worse harm the network efficiency. Even though the optimal length of the sleep session could be unidentified, we employ a powerful and quite simple learning from experience technique, namely the Learning Automata (LAs), to support the ONUs to take the best possible decisions based on the current network status. According to extensive simulation experiments, the applied enhancement succeeds to offer notable energy savings without overshadowing the network performance.

The remainder of this paper is organized as follows. Section II describes the architecture of the Ethernet-based PONs. In Section III, existing research efforts on energy management in PONs are outlined. Section IV analyzes the proposed energy efficient scheme, while Section V presents evaluation results accompanied by detailed comments. Finally, Section VI concludes this paper.

II. Ethernet Passive Optical Networks

The principle role of a PON is to provide subscribers with access to the backbone network. Typically formed in a tree shape, a PON architecture consists of an Optical Line Terminal (OLT), which is located at the Central Office (CO), and multiple optical network units (ONUs), which are located near the subscribers premises. Each ONU connects numerous subscribers, while the OLT is linked with all the ONUs via optical fibers. A passive optical splitter/combiner facilitates the PON interconnections by allowing the combination of various

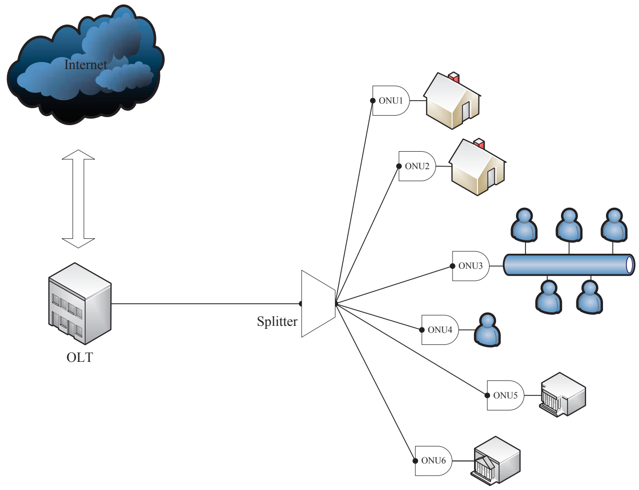

Fig. 1. PON Architecture.

optical signals from the subsribers' side to the CO's side. At the same time, it splits optical signals that are sent from the OLT to multiple signal copies that are destined to each ONU. In addition, the optical splitter/combiner does not consume power since it is a passive device. Each fiber is connected to a single ONU, creating a point-to-multipoint architecture, and at the same time providing an all-optical path without involving any kind of conversion. Figure 1 demonstrates the PON architecture that is being used at most.

Subscribers and the CO are able to communicate in a two-way fashion by using two different wavelengths. The downstream direction is used by the OLT in order to broadcast optical signals to the ONUs. In a tree topology the broadcast nature of the downlink direction permits the ONUs to receive all data; however, each ONU is able to select the appropriate data flows. The upstream direction carries out data from the ONUs to the OLT. Nonetheless, a common optical fiber is shared among all ONUs; this is the part that connects the OLT with the optical splitter/combiner. Hence, coordination is needed between ONUs in order to avoid collisions. In Ethernet-based PONs the IEEE 802.3ah has proposed the multipoint control protocol (MPCP) [4]. MPCP involves two important control messages: the GATE message and the REPORT message. The GATE message is employed by the OLT so as to inform a specific ONU about transmission opportunities and properties, such as the transmission duration and the time of the transmission. Typically, a control channel is utilized to transfer control messages such as the GATE message. On the other hand, REPORT messages are used by the ONUs to inform the OLT about their queue status. The REPORT message is piggybacked inside the data frame. Once the ONU receives the GATE message begins to transmit data according to the GATE directions. If no uplink traffic exists the ONU sends an empty REPORT message indicating that it remains idle. This announcement could trigger a potential sleep session in the ONU side.

III. Related Work

Although numerous energy efficient techniques regarding wireless communications have made their appearance in the literature, the development of low-energy strategies for access networks has not received the same kind of progress. Scientific works [5], [6] that present comparisons between different types of access networks, also identify a notable pitfall concerning the energy efficiency in PONs. Recent recommendations from the 10G-EPON Task Force, which propose a low power state for PON equipments, prove that energy consumption in PONs is of fundamental importance [7]. However, the majority of the energy-aware schemes found in the literature either suggest hardware-based alterations [8], [9], which may scale up the network implementation cost, or energy-aware schemes that neglect the current traffic conditions [10]. In this work, we endeavor to cover this gap by designing an adaptive enhancement for the ONUs in order to ensure high energy savings with no negative effect on service provisioning.

IV. Adaptive Power Management

A. Challenges and Objectives

The design of a robust power management scheme entails the addressing of considerable challenges. First, the applied scheme should ensure real energy efficiency. Each ONU should be carefully treated so as to be switched in a sleep or normal mode in a way that the energy savings become as much as possible. The power mode handling in the ONUs should guarantee that the network operation remains acceptable without being overshadowing by the ONU power mode changes. This challenge could be further extended by considering that a poor scheme could induce unexpected high data delivery delays due to missed sleep periods. In parallel, it is important to ensure that the network throughput remains in high levels even though a power management scheme runs in the background. For instance, a thoughtless enhancement of the bandwidth management process, e.g., the MPCP, with a multitude extra control messages is not always beneficial for the network performance. To this end, the network operation should be kept undisturbed when a power management scheme is in use in terms of data delivery delay and network throughput.

In the light of the aforementioned challenges, this work aims at achieving the following objectives. Given that the access network traffic is rather bursty [11], the proposed power management scheme should be capable of setting idle ONUs in sleep mode for long periods. Furthermore, the introduced scheme should be adaptive and able to learn from the behavior of each ONU. This ensures that the learning from experience rationale behind our technique could facilitate the training so as to maximize the energy savings by suitably determining the sleep period of each ONU. To such a degree, the main objective of the proposed scheme is to estimate the proper sleep period of each individual ONU when a sleep opportunity occurs, i.e., when an ONU is noticed to be idle. Concurrently, the introduced scheme operates in a dynamic fashion, which means that it is capable of directly adapting to unexpected network changes. In addition, the procedure of the power management scheme keeps the pure MPCP intact, without employing additional or secondary control messages.

B. Learning From Experience Enhancement

In this work, we propose a power management scheme which is effectively enhanced with an adaptive learning from experience technique. While a variety of potential learning methods could be utilized, the LAs exhibit a unique feature; they are able to directly adapt to changes functioning in a simple way [12]. Optical networking implies fast, quick, and direct decision making so the decision-aware devices should be enforced with efficient but simple thinking components. LAs combine fast and efficient decision determination. They have been successfully applied in many problems in networking and communications technology, e.g., [13], hence, they have been selected as the main learning from experience mechanism to support the ONUs towards the sleep period determination.

A LA is a finite state machine that interacts with a stochastic environment aiming at learning the optimal action offered by the environment via a training process [14]. The LA exchanges information with the environment in a two-way fashion. In particular, the device in which the LA operates maintains a set of possible actions/decisions. Whenever the device requests an action, the LA selects a specific action from the pool of decisions. When the device performs the selected action, it receives the feedback information, probably from the environment, and then it forwards the feedback to the LA module. In the next step, the LA properly process the feedback order to adapt to the environment's changes. Based on the current status, the LA computes the next action and informs the devices as long as it receives a request. Obviously, the main goal of the LA is to determine the optimal action. If the optimal action can be measured, i.e., due to frequent changes, the LA tries to reach the best possible action from the pool of possible ones.

C. Model Design and Formulation

As previously mentioned the LA will empower the ONU in order to strengthen its decisions about the length of the sleep period. In this way, the LA is requested for a decision whenever the ONU initiates a sleep period. In this work, we demonstrate the proposed power management scheme in the doze mode, i.e., we assume that an ONU is capable of turning off the transmitter when there is absence of uplink traffic. Hence, the environment is the ONU uplink interface. Moreover, the action pool contains decisions considering the length of the doze session. The action pool for each ONU is represented by the set $A = \{a_1, a_2, ...a_m\}$. The set contains m possible actions. According to the standard, the maximum sleep period of an ONU is 50 msec [4]. This is attached to the periodical MPCP REPORT messages to the OLT for synchronization and bandwidth monitoring reasons. In order to keep the model precise, we devise $m = 500$ different actions from 0.1 msec to 50 msec with step 0.1 msec. Hence, the action a_1, which represents the first possible action implies 0.1 msec sleep time, the action a_2, which represents the second possible action dictates 0.2 msec sleep time, and the final possible action, a_m corresponds to the maximum 50 msec sleep time.

The proposed model operates in a distributed way. In essence, an independent LA is incorporated in each ONU. Hence, each ONU is able to determine its sleep time independently of any other network component in the PON. For each ONU, f, the LA structure is divided into two parts, namely the *learning* and the *estimation* part. The learning part is responsible of updating the status information of the model in order to adapt to network changes. For this purpose, the LA maintains a probability vector, denoted by P^f, where a probability value is attributed to each possible action. Thus, the probability vector is formed as follows: $P^f(K) = \{p_1^f(K), p_2^f(K), ..., p_m^f(K)\}$. The parameter K indicates the Kth sleep session. Obviously, it holds that for each f, $\sum_{i=1}^{m} p_i(K) = 1$. The dynamic nature behind the LA-based model lies in the probability vector update. Upon completing a sleep session, the ONU informs the LA module about the actual time the previous sleep session elapsed. This time is actually the feedback from the environment to the LA. The learning part of the module exploits the feedback by increasing the probability of the action that corresponds to the feedback. At the same time, all other probabilities are slightly reduced. By doing so, the LA is trained in order to reach the optimal decision based on the received feedback information.

The estimation part is triggered when the ONU initiates a sleep period. The LA produces a random variable based on the defined probability vector and an action is selected. This action corresponds to a specific sleep duration; hence the ONU enters into the sleep period for this time.

D. Operation

The operation of the proposed adaptive scheme is presented in both the OLT and ONU sides. The Algorithm 1 describes the scheme's operation in the OLT side. Initially, all ONUs are considered active. The OLT sends the GATE message to all ONUs and based on the received REPORT message perceives whether an ONU is changed from the active to sleep state. The OLT is able to be aware of the defined sleep period by the REPORT message. It is worth mentioning that the decision regarding the sleep time duration is taken in the ONU side, while the OLT becomes aware of that by the REPORT message. Upon an empty REPORT message is received the OLT knows a) the owner of this message is now in sleep state and b) the wake-up time. Hence, it is capable of scheduling the consequent GATE message. However, the sleep time period could be lesser than the round trip time of the ONU plus the transmission time of the control messages. So, the OLT postpones the transmission of the GATE message only if the sleep period is large.

The main operation of the adaptive scheme is revealed within Algorithm 2. A sleep session initialization occurs when an ONU, let it be the ONU_f, receives a GATE message and

Algorithm 1 OLT: The Adaptive Power Management Scheme

INPUT: The round trip time (RTT) vector of each ONU, the GATE transmission time ($GATETT$), and the REPORT transmission time ($REPORTTT$)
OUTPUT: The updated MPCP
Set all ONUs in active state
for each cycle **do**
  for each active ONU_f **do**
    OLT sends the GATE message
    OLT receives the REPORT message from the ONU_f
    if REPORT message is empty **then**
      OLT is aware of the sleep time duration (STD_f) by the REPORT message
      if $STD_f > RTT_f + GATETT + REPORTTT$ **then**
        OLT schedules the transmission of the GATE message to the ONU_f in $STD_f - GATETT - REPORTTT - RTT_f$
        OLT sets ONU_f in sleep state
      else
        OLT sends the GATE message immediately
      end if
    end if
  end for
end for

Algorithm 2 ONU: The Adaptive Power Management Scheme

INPUT: The convergence speed parameters L and α, the action pool A, the probability vector $P^f(K)$
OUTPUT: The sleep time duration (STD_f), the updated probability vector $P^f(K+1)$
Initialize the probability vector P^f, $p_i = 1/m$, where $1 \leq i \leq m$.
for the Kth sleep session initialization **do**
  The ONU has received a GATE message from the OLT
  The ONU found no uplink traffic waiting in its queue
  Select randomly an action a_s from the action pool A based on the given probability distribution P^f of each possible action. The selected action a_s corresponds to STD_f time period
  The ONU sends an empty REPORT message to the OLT including its defined STD_f
  The ONU enters the sleep session for a duration equal to STD_f
end for
for the Kth sleep session termination **do**
  The ONU wakes up
  The ONU receives the following GATE message from the OLT
  The ONU calculates the feedback, i.e., the actual/proper sleep period, let it a_o
  Set $p_i(K+1) = p_i(K) - L(p_i(K) - \alpha), \forall i \neq o$
  Set $p_o(K+1) = p_o(K) + L\sum_{i \neq o}(p_i(K) - \alpha)$
  if no uplink traffic is observed **then**
    The ONU initializes a new ($(K+1)th$) sleep session
  end if
end for

observes no uplink traffic in its buffer. Accordingly, it enters a sleep session, where the enhanced LA decides about its length. In particular, as described in the first for-end loop, the LA selects the next best action, i.e., a_o, from the action pool, i.e., A, that corresponds to STD_f time periods and then the ONU informs the OLT that a) it enters a sleep session by sending to OLT an empty REPORT and b) its length by sending the STD_f as well. Upon it wakes-up, the ONU receives the GATE message, as described previously in Algorithm 1. Then it calculates the feedback based on the actual time period the previous sleep session actually elapsed. That feedback indicates the action a_o as the optimal one and therefore the LA updates its probability distribution appropriately. The parameter L dictates the speed of the automaton convergence. The lower the value of L,the more accurate the estimation made by the automaton. However, this fact comes at the expense of the convergence speed. The role of the α parameter is to prevent the probabilities of unpopular actions from taking values in the neighborhood of zero to increase the adaptivity of the automaton. Finally, the ONU decides whether it re-initializes a sleep session based on the existing uplink traffic. If so, the first for loop is repeated.

V. Performance Evaluation

This Section is devoted to the performance evaluation of the proposed scheme.

A. Assessment Environment

A 10G-EPON architecture has been carefully designed in Matlab in order to study the impact of the applied adaptability to the network efficiency. In essence, a set of comparative simulation results is presented, where the effectiveness of the introduced adaptive mechanism, designated as 'adaptive scheme', is compared to a generic scheme having predefined and fixed sleep period duration for each sleep session, known as 'fixed scheme'. Furthermore, in order to provide a more challenging assessment the fixed scheme adjusts the sleep period in accordance to the number of ONUs participating in the network with the following formula: $Sleeptimeduration = N \cdot 0.1ms$, where N denotes the number of ONUs. The rationale behind this arrangement has to do with the overhead of the control messaged appeared in network when the number of ONUs becomes large. Due to heavy load the OLT may induce delays in sending the GATE messages to the various ONUs resulting in increasing the duration of the potential sleep period sessions. Nonetheless, the sleep time duration of the fixed scheme remains stable and fixed for the whole simulation experiment, whereas the adaptive scheme is capable of adjusting the duration of each sleep session in a dynamic

Parameter	Value
ONUs distances	$U[1000, 20000] meters$
Transmission rate (uplink and downlink)	10 Gbps
Guard time	0.5μsec
Grant policy	Limited sizing
Grant window	10000 bytes
Power consumption (normal mode)	4.69W
Power consumption (sleep mode)	1.7W
Simulation time	10 sec

TABLE I
MAIN SIMULATION PARAMETERS

fashion.

The designed architecture consists of up to 30 ONUs, deployed in various locations. In particular, we consider a uniform distribution to define the ONUs' distance from the OLT within $[1000, 20000]$ meters. That assumption stimulates how realistic the assessment is, since the round trip times of each ONU present a high degree of differentiation in actual PON infrastructures. Regarding the applied polling scheme the literature presents two main techniques, the *interleaved polling* and the *interleaved polling with stop* [15]. Since the latter technique induces an overhead (propagation) time of at least an RTT, because the OLT waits to receive the REPORT message from the last ONU in a cycle before polling the first ONU in the next cycle, the interleaved polling technique is adopted, where the OLT can issue the grants of all ONUs in a dynamic fashion, i.e., in a first come first served way. In addition, the Grant window follows the limited grant sizing with maximum grant equal to 10000 Bytes.

The traffic model assumed produces both upstream and downstream traffic based on a Poisson distribution where the generated frames are uniformly produced Ethernet frames of $U[64, 1518]$ Bytes. Each ONU is equipped with a large enough buffer such that no buffer drops occur. Moreover, it is considered that the energy consumed in the buffer is negligible. According to the standard, both GRANT and REPORT messages have length equal to 64 Bytes. A small guard time is assumed between consecutive bandwidth allocations of 0.5 μsec. The power consumption of an ONU is set to 4.69W and 1.7W under normal and (doze) mode respectively. Table I summarizes the main simulation parameters.

The transmission rates of both directions are considered equal to 10 Gbps. Each simulation experiment has been conducted for 10 sec of network operation. Three critical performance metrics have been investigated based on the remarks presented in the Section IV-A. In particular, the evaluation process measures a) the mean ONU consumption, b) the mean packet delay, and c) the networks throughput. Our main goal is related to the behavior of the above metrics, particularly to determine the trade-off between the power reduction and the network efficiency when the proposed scheme is applied.

B. Numerical Results

First, the mean power consumption is examined. Figure 2a illustrates the mean ONU consumption when the traffic load varies, while Figure 2b shows the mean ONU consumption when the number of ONUs increases. In the former figure the number of ONUs remain stable and equal to 15. In the latter figure the load is kept steady and equal to 1 packet/msec. In general, the power consumption increases as the traffic load becomes denser. This is attached to the fact that ONU sleep opportunities are minimized under heavy load, because a (doze) sleep session initialization entails that no (uplink) traffic exists in the ONU interface. However, it is important to note that the proposed scheme achieves considerable improvements in terms of power reduction. In essence, it seems capable of reducing the mean power consumption by 30% to 40% irregularly of the network traffic.

Similar results are obtained in Figure 2b, where the improvements of applying the adaptive scheme reach 30% to 35%. The reason behind this upgrade lies in the adaptive nature of the enhancement. It is clear that the LAs, running in a distributed manner in the ONUs, play a beneficial role towards the advancement of the network efficiency. The decisions the LA support lead the ONUs to correct sleep period time determination. Thus, it is feasible to estimate the most proper choice to support a sleep session initialization without knowing the traffic conditions a priori.

Nevertheless, the improvements in the power consumption area should be accompanied with analogous effectiveness in the network performance issues. Accordingly, the network performance is investigated in terms of mean packet delay and network throughput. The mean packet delay measurement is depicted in Figure 2c as the load varies and in Figure 3a as the number of ONUs alters. It is easy to observe that both figures reveal the same performance between the two schemes. In other words, the use of the adaptive scheme does not induce extra delay. Hence, it succeeds to offer considerable energy savings without harming the mean packet delay.

Another observation is related to the network throughput, since the applied scheme sustains the same level of data delivery to the end users. Figure 3b reveals the observed network throughput when the traffic load varies, while Figure 3c illustrates the same metric against a varying number of ONUs. It is easy to notice that a) the network throughput continuously gains ground as the either the load or the number of ONUs increases, and that b) both schemes offer the same amount of delivered traffic. Once more, the adaptive scheme proves its superiority, since it guarantees undisputed service provisioning with lower energy consumption.

In a nutshell, the interpretation of the evaluation results indicate that the proposed scheme could be adopted without causing service disorientation, while important energy savings are reserved. The scheme could be utilized either under various network conditions or with numerous ONU devices.

VI. CONCLUSIONS

An energy efficient power management scheme for Ethernet PONs was proposed. In order to enable the ONUs to determine the duration of the sleep period, we devised a learning from experience technique based on LAs. The dynamic arrangement

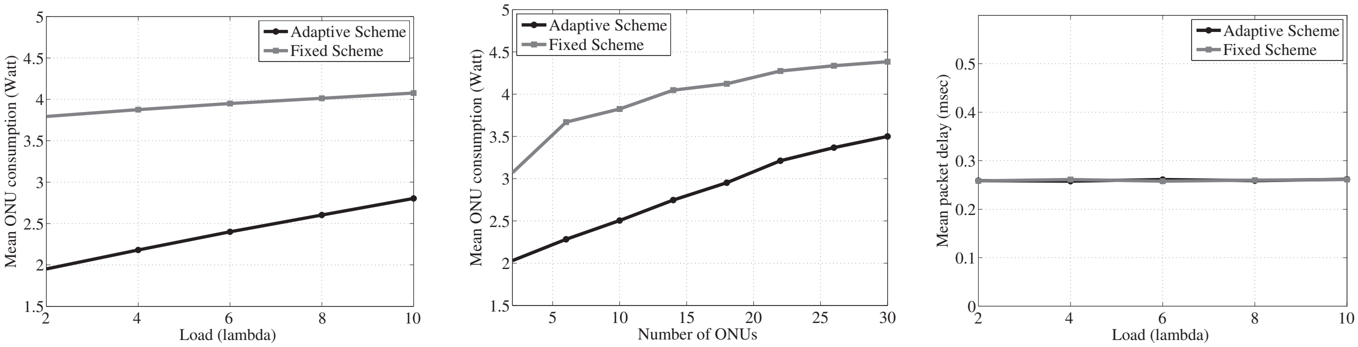

Fig. 2. a) Average power consumption vs Traffic Load, b) Average power consumption vs Number of ONUs, and c) Mean packet delay vs Traffic Load.

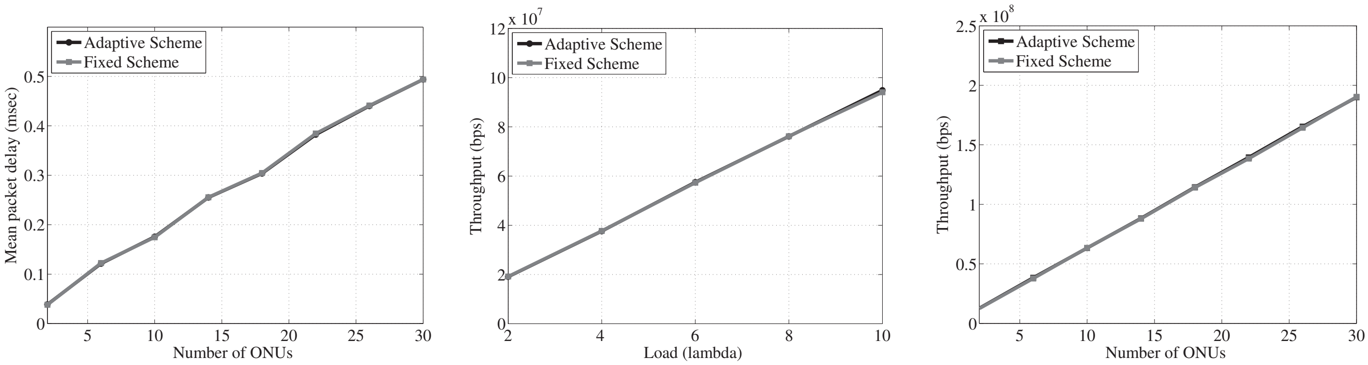

Fig. 3. a) Mean packet delay vs Number of ONUs., b) Throughput vs Traffic Load, and c) Throughput vs Number of ONUs.

of the LA mechanism is proved efficient and effective via realistic simulation experiments, since it is capable of providing considerable energy savings, compared to a competitive fixed power management scheme, without overshadowing the network performance. Based on our findings, the applied enhancement could offer up to 40% energy reduction under multiple scenarios, where either the traffic load or the number of ONUs changes.

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