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A low-overhead switched-mode Energy saving strategy for OFDMA-PON downstream transmission

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ABSTRACT

Green networks and energy saving have become important topics of worldwide concern and attracted intensive attention from both academia and industry. As orthogonal frequency division multiplexing access passive optical network (OFDMA-PON) employs more advanced and energy-consuming digital signal processing (DSP) techniques than other PON systems, it is of critical importance to improve the energy efficiency of OFDMA-PONs. In this paper, we propose a switched-mode energy saving strategy with low overhead for OFDMA-PON downstream transmission. By embedding information in the short training sequences (STSs) of the OFDM frame preamble, the STSs serve a twofold purpose: providing time synchronization and carrying the information with regard to the destination of the frame, hence eliminating the need for extra upper-layer control or information exchange between OLT and ONU. As STS is an inherent part of the OFDM frame, the proposed scheme requires little extra overhead in transmission time and hardware cost. The ONU continues the subsequent processing only when it is the intended receiver, while the unintended ONUs drop the frame and stands by to save energy. In order to achieve a tradeoff between energy saving and delay performance, the scheme switches between single-ONU mode and team mode where either a single ONU or a team of ONUs are the targeted receivers. We verify the feasibility of proposed scheme through experiments and evaluate the performance in terms of energy saving and packet delay by simulations. The results indicate that substantial energy can be saved compared with conventional OFDMA-PON systems.

1. Introduction

Telecommunication networks and broadband access consumes huge amount of energy [1–3]. It is worth noting that around 70% of overall Internet energy consumption is consumed by access network equipment [4]. With the ever-increasing data traffic demands, energy saving in access networks have become an important issue of worldwide concern in recent years. Passive Optical Network (PON) is considered as one of the most power-efficient solutions in terms of energy consumption per transmission bit [5]. In particular, orthogonal frequency division multiplexing access PON (OFDMA-PON) has emerged as an attractive candidate for next-generation broadband optical access due to its numerous advantages such as high spectral efficiency, strong robustness to chromatic dispersion, and great flexibility in dynamic bandwidth allocation [6,7]. Several OFDMA-PON systems capable of ultra-high data rates have been reported and demonstrated [8,9].

Like other PONs, the optical line terminal (OLT) and optical network units (ONUs) are the active equipments in OFDMA-PON. With the increase of the number of subscribers, ONUs located at the user premises dominate a major portion of the overall power consumption. Furthermore, the ONUs in OFDMA-PON employ a great number of advanced and energy-consuming digital signal processing (DSP) components [10], such as the energy-intensive fast Fourier transform (FFT) module. As a result, ONU side energy saving is a challenging and critical task for OFDMA-PON.

Substantial efforts have been devoted to making PON more energy-efficient during past years. Among the existing approaches, a class of schemes based on the use of sleep/doze modes has been proposed, which turns off the transmitter and/or receiver of idle ONUs to save energy [11,12]. Lately, the sleep mode mechanism has been applied to OFDMA-PON [13]. However, such schemes induce a service disruption risk when downstream traffic arrives and require a very precise sleep control. To convey the accurate power-on/off time indication, there is an inevitable increase in MAC control cost, such as new protocol data units (PDUs)

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introduced in the three-way handshake process between OLT and ONUs [11].

Meanwhile, from the perspective of physical layer, several schemes for improving the energy efficiency of OFDMA-PON have been proposed by taking the inherent features of OFDM into account [10,15,16]. The main idea is to adaptively enable/disable processing modules according to the dynamic network load. For example, the energy-efficient OFDM transceiver proposed in [15] adaptively tunes the signal bandwidth and sampling rate, and selectively powers off individual block of parallel modules based on instant traffic load. Similarly, in [10], the authors propose a modular DSP design for both OLT and ONUs. The DSP modules are adjusted or switched-off when lower bit rates are required. While in [16], a time-domain interleaved OFDM technique is proposed to reduce the power consumption of OFDM-PONs by reducing the sampling rate and the FFT size of the ONUs. Note that such solutions pose challenges to implementation as it requires special design for the hardware architecture.

More recently, in Ref. [17], the authors propose an energy-efficient selective sampling receiver for OFDMA-PON, which only samples when the incoming data is targeted to the ONU and stays in standby during the rest of the time. Nevertheless, the energy saving comes at a cost as specially arranged orthogonal pseudorandom noise (PN) sequences need to be added in the frame head to identify the intended ONU.

In this paper, we focus on reducing the power consumption of the ONUs for OFDMA-PON downstream transmission and propose a switched-mode energy saving strategy. To the best of our knowledge, this is the first work to leverage on the short training symbols (STS), which is an inherent part of an OFDM frame, to achieve energy saving without extra cost in transmission of MAC control message or overhead in the frame head. The proposed scheme switches between two modes according to the incoming traffic status to obtain a trade-off between energy-efficiency and packet delay performance. It is shown that ~70% energy saving can be achieved on the ONU side during the downstream transmission compared to conventional OFDMA-PONs under heavy traffic load.

2. Proposed energy saving scheme

2.1. Energy-efficient receiving modes

In this paper, we propose two energy-efficient receiving modes for OFDMA-PON downstream transmission, including single-ONU mode and team mode. As shown in Fig. 1, the ONUs marked in yellow are the intended receivers.

Under single-ONU mode, each ONU is treated as an independent entity, and the frame is destined to only one particular ONU. While under team mode, the ONUs are divided into several teams. M ONUs form a team and share a common team identification number. The OLT packs downstream data destined to ONUs in the same team and form a complete OFDM frame to be transmitted. The frame is destined to all the M ONUs belonging to the intended team. The system can switch between the two modes to meet different requirements of energy saving and delay under various scenarios.

Under team mode, OFDMA is realized within a group of ONUs. The available bandwidth can be shared with dynamic bandwidth allocation among individual ONUs under the same team. Note that, when M takes the value of the total number of ONUs N, the proposed scheme is reduced to conventional OFDMA-PON. On the other hand, single-ONU mode can be seen as a special case of team mode with $M = 1$. This mode compromises the fine granularity feature in resource allocation of OFDMA and is suitable for scenarios where energy saving holds priority over bandwidth allocation flexibility. Therefore, by setting the numbers of ONUs per team, a tradeoff can be achieved between energy saving and flexibility of OFDMA.

2.2. Physical layer data frame format

The proposed frame structure with specially designed preamble used in this work is shown in Fig. 2. The preamble consists of 10 cycles of short training sequence (STS) of 16 samples and 2 identical long training sequences (LTS) of 64 samples preceded by a

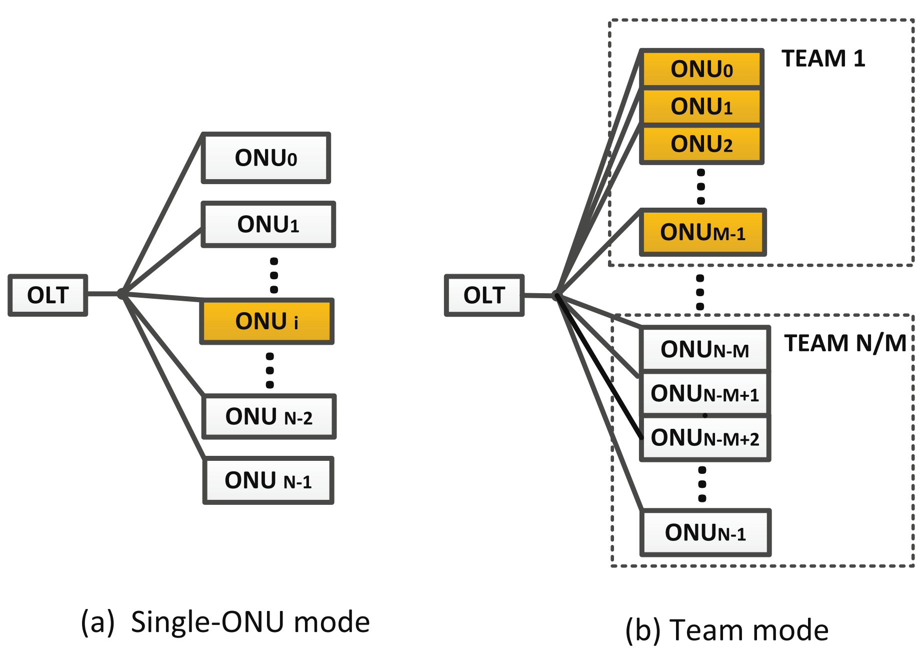


Fig. 1. Structure of two energy-efficient modes.

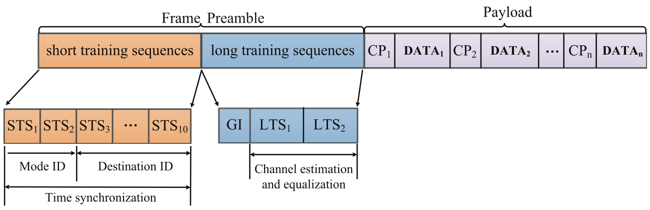


Fig. 2. Proposed frame structure.

guard interval (GI) composed of 32 samples from the last samples of the LTS. This structure is similar to that adopted in wireless OFDM system standards such as WLAN IEEE 802.11 a/g [18] and WMAN IEEE 802.16-2004 [19], and also in optical OFDM systems [20]. In general, the OFDM receivers rely on STS for synchronization and LTS for channel estimation and equalization.

The difference between the proposed and conventional frames lies in that instead of 10 identical STSs, the STSs of the proposed preamble have the same pattern, but different polarities, i.e., $STS_i \in \{+STS, -STS\}$ ($i = 1,\ldots,10$). While the periodicity of the STSs helps to find the position and accomplish synchronization, the polarity of the STSs are exploited to carry information. Namely, STS represents '1' and −STS represents '0'. As shown in Fig. 2, the STSs are divided into two parts: the energy-efficient modes identification code (mode ID) and the destination ID. The mode ID is used to identify the chosen mode, and the destination ID is to indicate the destination of the frame, which is the index number of either the ONU or the team.

For synchronization, the receiver performs cross-correlation between the received frame and short training sequences. The cross-correlator outputs exhibit a positive or negative peak every 16 samples. The position of the peaks are used to accomplish time synchronization, while the signs of the peaks are used to recover the information carried in the STSs. The positive peak denotes '1' and the negative peak denotes '0'.

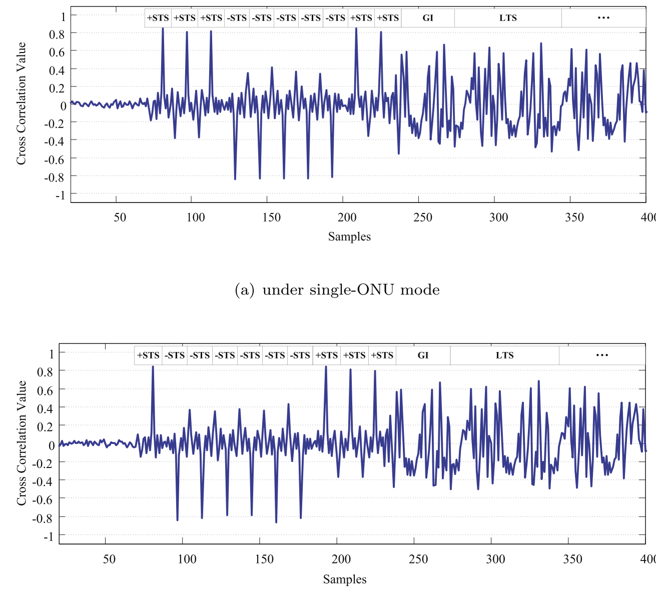
For example, the OLT transmitter packs data destined to a particular ONU in a downstream frame. It sets [STS STS | STS −STS −STS −STS −STS −STS STS STS] in the front part of the preamble and broadcast the frame to all ONUs. Every ONU looks at the downstream frame preamble to maintain synchronization and extracts the information from the correlator output as shown in Fig. 3. The recovered information is '11|10000011', where the first two bits '11' indicates single-ONU mode, and the rest bits '10000011' indicates the intended ONU number is 131. Likewise, [STS −STS | −STS −STS −STS −STS −STS STS STS STS] in the preamble would be recovered as '10|00000111', which indicates that the frame is destined to all the ONUs in team 7 as '10' denotes team mode.

Only when the ONU is the intended receiver of the frame does the ONU resume ADC sampling and the rest DSP operations including FFT and demodulation. Otherwise, it drops the frame and stands by until next frame. In this way, by turning off the energy-intensive DSP modules of the standby ONUs, significant energy saving can be achieved. As the training sequence is an inherent part of an OFDM frame and the cross-correlator is an indispensable part of the receiver for synchronization, the proposed scheme requires little extra overhead in transmission time and hardware cost.

2.3. Switched-mode energy saving strategy

During a downstream frame broadcasted by the OLT, the energy consumption of all the ONUs for conventional OFDMA-PON is given by

$$E_t = N(P_{front} + P_{ADC} + P_{DSP})T_{frame} \tag{1}$$



(a) under single-ONU mode

(b) under team mode

Fig. 3. Examples of the amplitude of the cross-correlator output at the ONU receiver.

where N is the number of ONUs and T_{frame} is the OFDM frame duration time. P_{front} is the total power consumption of the front-end components such as the photodetectors and amplifiers. P_{ADC} and P_{DSP} is the power consumption of ADC sampling and digital processing modules including FFT, equalization and so on, respectively.

Under single-ONU mode, only one ONU is the intended receiver of the frame while the other $N-1$ ONUs can switch into standby mode and power off the subsequent energy-consuming modules. Hence, the energy consumption of all ONUs under single-ONU mode can be calculated as

$$\begin{aligned} E_m^1 &= NP_{front}T_{frame} + (P_{ADC} + P_{DSP})T_{frame} \\ &\quad + (N-1)\left[P_{ADC}T_{syn} + P_{standby}(T_{frame} - T_{syn})\right] + E_{control} \end{aligned} \tag{2}$$

where T_{syn} is the time spent for synchronization process. $P_{standby}$ is the energy consumption of an ONU in standby state. $E_{control}$ is the energy consumption of the control circuits for an ONU to stand by or wake up. Based on [11], this consumption can be considered negligible compared to other items.

Similarly, the energy consumption under team mode can be calculated as

$$\begin{aligned} E_m^2 &= NP_{front}T_{frame} + M(P_{ADC} + P_{DSP})T_{frame} \\ &\quad + (N-M)\left[P_{ADC}T_{syn} + P_{standby}(T_{frame} - T_{syn})\right] + E_{control} \end{aligned} \tag{3}$$

which indicates that the energy-efficiency of team mode depends on the number of ONUs in each team.

In summary, single-ONU mode is more energy-efficient than team mode. However, it causes larger downstream packet delay as all the other ONUs have to wait. Based on the characteristics of the two modes, we propose a switched-mode energy saving strategy to achieve a balance between energy-efficiency and delay performances.

It is known that scheduling can be optimized to further reduce the energy consumption of PONs [13,14]. The basic idea is to schedule the downstream traffic to maximize the ONU sleep time without violating the delay constraints. For example, the OLT can schedule the downstream data transmission to a particular ONU in consecutive timeslots, so that the ONU sleep time can be prolonged to save energy. In this paper, the mode and the subsequent scheduling is decided based on the delay-sensitivity of the packets and the order of the ONUs for simplicity. For future work, the proposed scheme can be jointly optimized in combination with more sophisticated downstream packet scheduling algorithms, which needs to be further investigated.

To buffer the incoming downstream data for the ONUs, we set up two First-In-First-Out (FIFO) queues in the OLT for each ONU, which store the real-time and non-real-time packets, respectively. The real-time packets such as Voice of Internet Phone (VoIP) are delay-sensitive and thereby given high priority. Team mode is adopted for transmitting the real-time data to reduce the packet delay. On the other hand, since the non-real-time packets are delay-insensitive, the OLT switches to the single-ONU mode when transmitting the non-real-time data to maximize energy-saving.

Based on the aforementioned modes and frame structure, the working process of the proposed switched-mode energy saving strategy is summarized as follows.

- Step 1: Based on the downstream traffic load and delay sensitivity of the data, the OLT decides the energy-efficient mode and schedules the downstream packets.
- Step 2: According to the decision, the OLT sets the polarities of the STSs to carry information of the energy-efficient mode and destination ID.
- Step 3: Each ONU receiver performs cross-correlation between received frame and the STS to maintain synchronization. Meanwhile, the signs of the peaks in the correlator output are recorded and used to recover the information about the frame destination as described in Section 2.2.
- Step 4: If the ONU is the intended ONU under single-OUN mode or belongs to the intended team under team mode, it continues sampling and the subsequent processing. Otherwise, it discards the frame, turns off the DSP modules and stays in standby until next frame.

The flow charts of the procedures of OLT and ONU are shown as Fig. 4, respectively.

3. Performance evaluation

To verify the feasibility of the proposed scheme, we set up an OFDMA-PON transmission system over 25 km standard single-mode fiber (SSMF) as shown in Fig. 5. The real-time digital signal was converted to analog signal by a 12-bit DAC with a sampling rate of 4GSa/s. After passing through the electrical amplifier (EA), the low-pass filtered (LPF) electrical OFDM signal is converted to the optical domain by a single-mode 1550-nm distributed feedback (DFB) laser. The field programmable gate array (FPGA) chip which is Virtex-6 XC6VLX240T from Xilinx operates with a core clock of 125 MHz. From the experiment, it is shown that the frame destination embedded in the short training sequences can be identified clearly and hence be used to switch on/off the DSP modules of the ONUs for power saving as expected.

We assume there are totally 256 ONUs connected with the OLT, i.e., $N = 256$. The packet sizes in OLT buffer for each ONU obey Pareto distribution and a 125 μs frame length is considered in our experiment. At the OLT side, the data is mapped through 16 QAM modulation and then transferred to time domain by 64-point IFFT. A cyclic prefix of 16 samples is used to eliminate inter-symbol interference. 100 OFDM symbols are assumed for one OFDM frame. The OFDM samples are generated offline using MATLAB, and sent to the 12-bit DAC with a sampling rate of 4GSa/s. In the simulation, 30% of the downstream packets are assumed to be real-time and 70% non-real-time. The downstream packets are generated following Poisson distribution with parameter $\lambda = 12$ unless otherwise specified.

We referred to [10,21] for the energy consumption of the main front-end optical components. Xilinx XPower Analyzer, a build-in tool of ISE 14.5 for Xilinx FPGA development, is used to simulate the power consumption of DSP modules. In addition, the

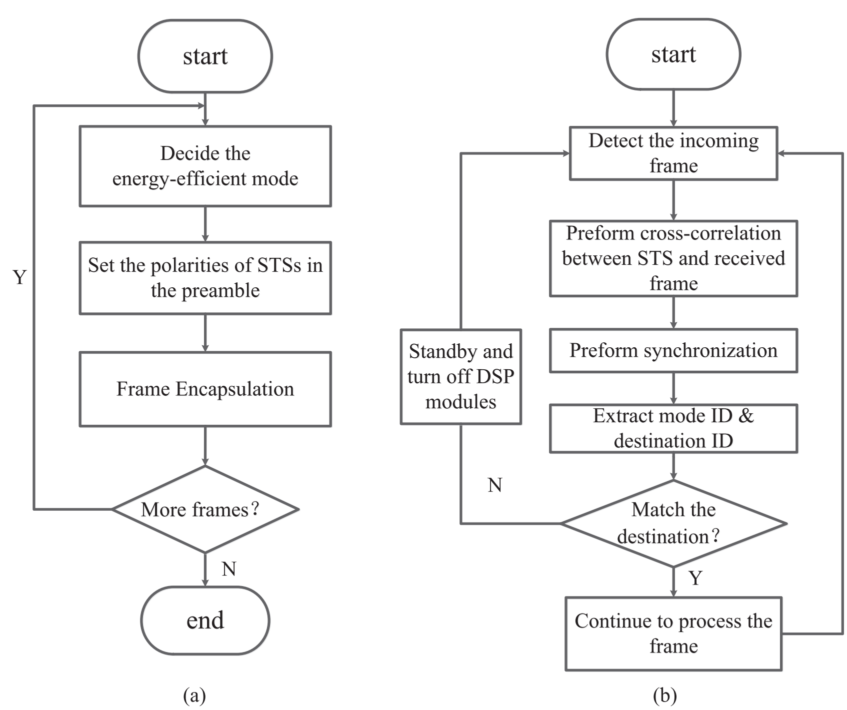


Fig. 4. Flow chart of (a) the procedure of OLT, (b) the procedure of ONU.

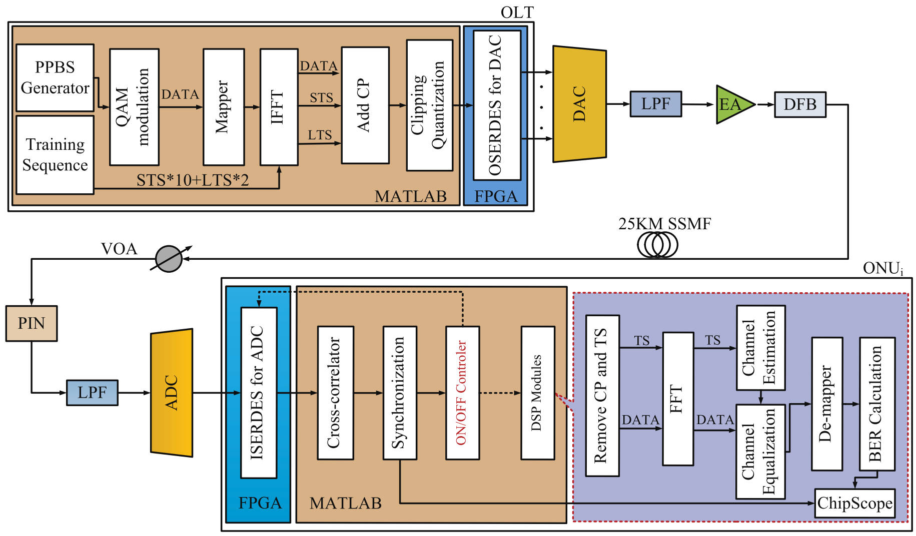


Fig. 5. Experiment setup.

standby/active control circuits are assumed to consume negligible power compared to other front-end analog circuits [11].

Firstly, we compare the energy consumption performance of the proposed two modes on the ONU side during downstream transmission under different traffic load levels. The performance of conventional OFDMA-PON is also given as a benchmark. As OFDMA is known for its fine granularity in resource allocation, the number of ONUs per team M can be set flexibly. As expected, the energy saving of team mode varies with the parameter M. Single-ONU mode is more energy-efficient than team mode, and the energy consumption of team mode increases with M. Specifically, more than 69% energy can be saved on the ONU side under single-ONU mode. At least 60%, 50% and 40% energy consumption can be saved when M takes value of 4, 16 and 32, respectively.

Fig. 7 shows the average delay versus traffic load with different M. The traffic load has a strong impact on the average delay. With the increase of the traffic load, the ONUs take more waiting time than under the light traffic load, hence a higher average delay would be imposed on the system. As we can see, the delay of single-ONU mode is longer than others and the performance gap increases as traffic load rises. Since each frame only includes an ONU's data, single-ONU mode leads to larger packet delay. Under team mode, M ONUs' data can be transmitted in one downstream frame simultaneously. Therefore, the average packet delay decreases with the increase of M.

From the results in Figs. 6 and Fig. 7, we can conclude that the single-ONU mode can save more energy but cost more delay. To achieve a balance between energy-efficiency and delay performances, we have proposed a switched-mode energy saving strategy which uses single-ONU mode to transmit non-real-time packets and team mode to transmit real-time packets.

Figs. 8 and 9 provide the performance of the switched-mode strategy in terms of the energy consumption and average delay. The energy consumption is normalized by that of the conventional OFDMA-PON. To evaluate the effectiveness of the proposed scheme, we have simulated over two of the most commonly used traffic patterns. The downstream packets are generated following Poisson distribution with parameter $\lambda = 12$ and exponential distribution with $\lambda = 10$, respectively. The performances of single-ONU and team mode with $M = 16$ are also given for comparison. It is clear that the switched-mode strategy provides a good tradeoff between energy saving and delay performance. Compared to conventional OFDMA-PON, significant energy-efficiency, i.e., ~70% energy saving ratio can be achieved on the ONU side in the downstream transmission under heavy traffic load.

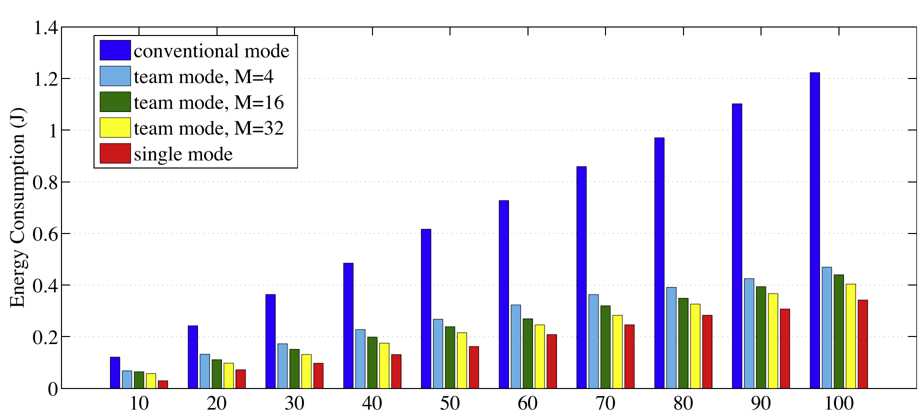


Fig. 6. Energy consumption with different numbers of ONUs per team.

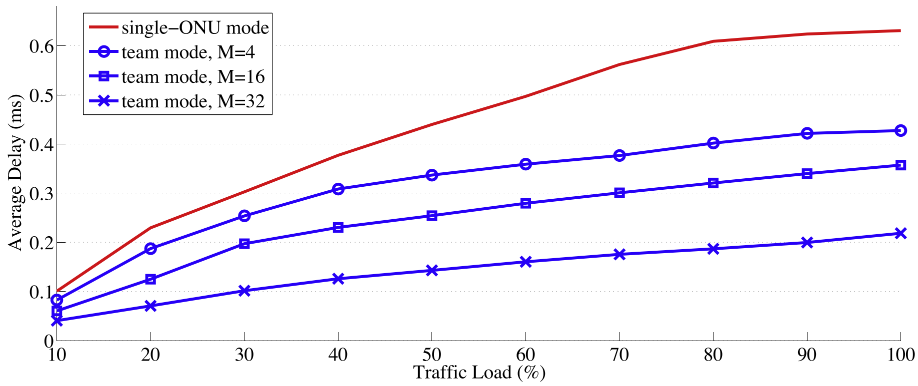
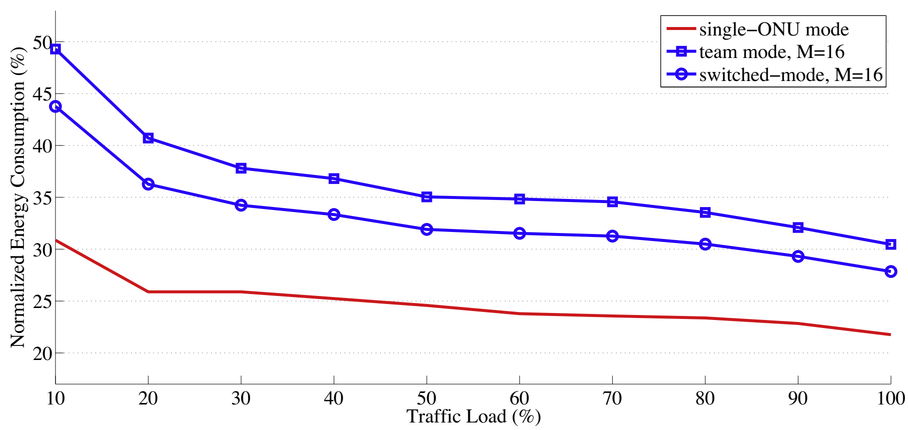
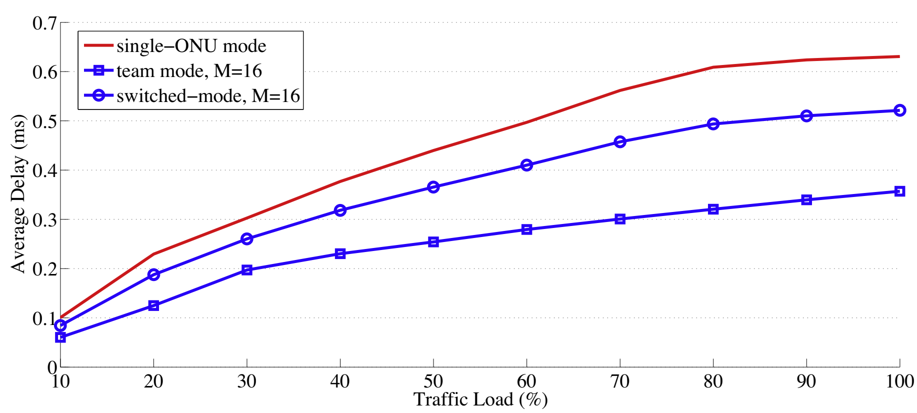


Fig. 7. Average delay with different numbers of ONUs per team.



(a) Normalized energy consumption

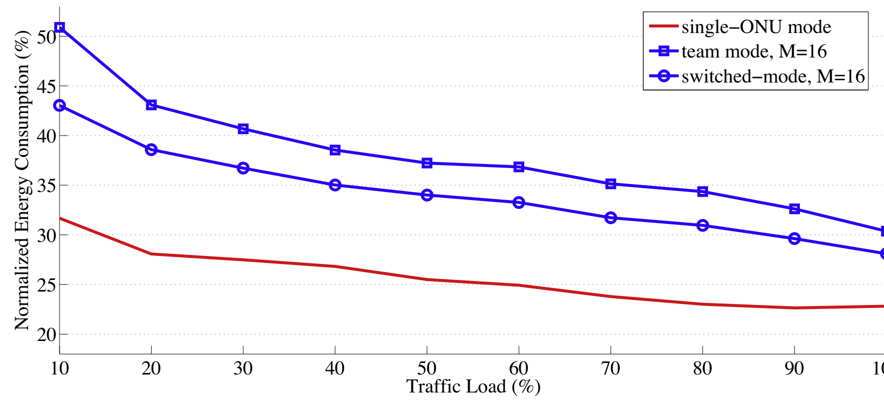


(b) Average delay

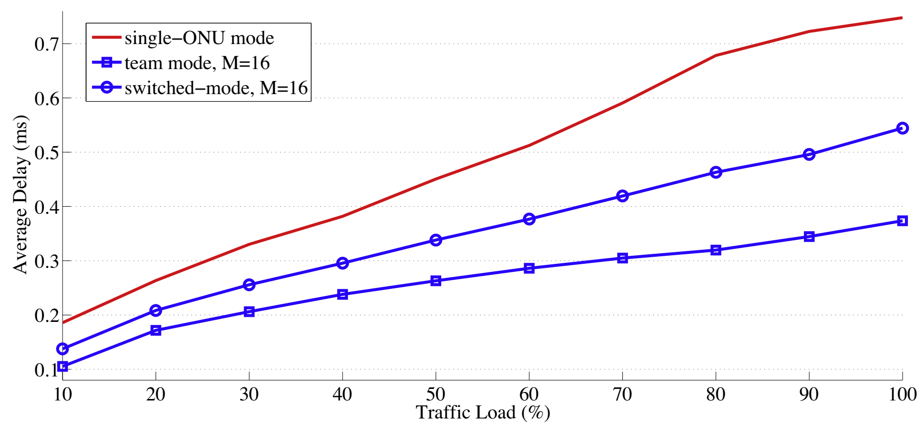
Fig. 8. Performance of the switched-mode strategy with Poisson distributed traffic pattern.

4. Conclusion

Energy saving is one of the critical issues in developing the next generation access network. With the focus on saving energy on the ONU side of OFDMA-PON systems, we have proposed a low-overhead energy saving scheme for OFDMA-PON downstream transmission. Instead of sending explicit information to notify ONU whether to turn on or to stand by, the OLT embeds the information of the frame destination in the short training sequences. In this way, the ONU is able to identify whether the incoming frame is intended for it without extra upper-layer control costs. Two modes are defined based on the number of intended ONUs. The unintended ONUs would drop the frame and turn off the subsequent DSP operations, which reduce the power consumption effectively.



(a) Normalized energy consumption



(b) Average delay

Fig. 9. Performance of the switched-mode strategy with exponential distributed traffic pattern.

Experiments have been set up to verify the feasibility of the proposed scheme. The simulation results show that the energy-efficiency has been enhanced greatly.

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