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Abstract. We propose a physical-layer energy-efficient receiving method based on selective sampling in an orthogonal frequency division multiplexing access passive optical network (OFDMA-PON). By using the special designed frame head, the receiver within an optical network unit (ONU) can identify the destination of the incoming frame. The receiver only samples at the time when the destination is in agreement with the ONU, while it stays in standby during the rest of the time. We clarify its feasibility through an experiment and analyze the downstream traffic delay by simulation. The results indicate that under limited delay conditions, ~60% energy can be saved compared with the traditional receiving method in the OFDMA-PON system with 512 ONUs. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.53.5.056106](https://doi.org/10.1117/1.OE.53.5.056106)]

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1 Introduction

With the emergence of bandwidth-intensive applications, such as high-definition television, cloud computing, big data services, and so on, the demands for large capacity in next generation passive optical networks (NG-PONs) are increasing continuously.¹ Besides, other requirements such as high customer fan-out, elastic bandwidth allocation, and high-energy efficiency are also desired. Orthogonal frequency division multiplexing (OFDM) technique features flexible bandwidth allocation and capability of supporting a large number of subscribers with high bit rates, which is a potential solution for NG-PONs.²⁻⁴ However, in the practical PON system, with the increase of subscribers, the energy consumed by optical network units (ONUs) has already taken up about 60% of the total energy consumption of PONs today.⁵

In a 10-Gb/s OFDMA-PON system, the average user rate is ~100 Mb/s, which only accounts for ~1% of the downstream line-rate.⁶ Nevertheless, in order to extract the user data, each ONU should demodulate the whole downlink data at the line rate. Thus, most components within an ONU have to be operated at the high-speed mode. For instance, in the 10-Gb/s downstream transmission, analog-to-digital convertor (ADC) needs to operate at least 5-GSamples/s with a 16-quadrature amplitude modulation (QAM) format. In such a case, the high-speed ADC almost dominates the power consumption of an ONU. Besides, the digital signal processing (DSP) module following the ADC also occupies a large percentage of the energy consumptions due to the complex electrical calculations.^{7,8} To deal with the high energy consumption problem, Kimura et al.^{9,10} introduced a dynamic signal-to-noise ratio management scheme, where calculation precision of the fast Fourier transform

(FFT) and inverse FFT (IFFT) is controlled to minimize energy consumptions.^{9,10} The scheme only considered the power of DSP while ignoring the energy-intensive DAC/ADC. Kanonakis and Tomkos¹¹ have proposed a framework to adjust optical line terminal (OLT)/ONU DSP modules according to real traffic flows.¹¹

We have demonstrated an energy-efficient ONU receiver based on selective sampling.¹² The proposed receiver is specially designed for OFDMA-PON since the energy-intensive component ADC is essential to demodulate the user data. 256 synchronization patterns generated by four orthogonal pseudorandom (PN) sequences are used to identify the destination of downlink frames. Only the ONU which coincides with the identified destination keeps working, while others are switched to standby mode until the timer expires. In this article, PN sequence design and detailed destination identification procedure are introduced. We also investigate the trade-off between energy saving and downlink packet delay by simulation. In order to decrease the packet delay, some ONUs are formed to a group to share a common destination. In this case, multiple ONUs' data can be transmitted in one downlink frame simultaneously while only one ONU's data can be transmitted in Ref. 12. The results indicate that under limited delay conditions, ~60% energy can be saved compared with traditional receiving method in an OFDMA-PON system with 512 ONUs.

2 Energy Saving Principle with Selective Sampling Receiver

Figure 1 shows the downstream operation with our proposed ONU receiver in OFDMA-PON. The proposed selective sampling receiver consists of a PIN/APD, two stages of amplifier, an ADC, a DSP module for the FFT and demodulation, and so on. In addition, a timer is added to power the on/off state of the ADC with the help of a synchronization module. The synchronization is based on the special

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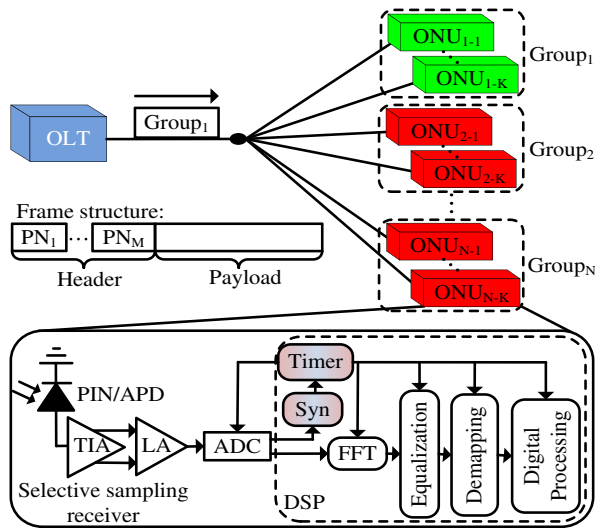


Fig. 1 Orthogonal frequency division multiplexing access passive optical network downstream operation with our proposed selective sampling receiver. TIA: trans-impedance amplifier; LA: linear amplifier.

designed header, which is shown in Fig. 1. There are M orthogonal PN sequences in the header, which means that totally M^M different destinations can be identified by varying the arrangement of M PN sequences. Note that one PN sequence can be repeated M times to achieve a synchronization pattern since all the PN sequences are orthogonal to each other. Through this PN designed method, we can obtain lots of orthogonal PN sequences. So, each ONU can be assigned a particular synchronization pattern.

Then the energy saving principle with our proposed selective sampling receiver is illustrated as follows. The OFDM frame has a fixed length of $125 \mu\text{m}$ and consists of a payload and a header. Based on the special designed header, the destination of downstream frames can be identified. Only when the identified destination corresponds to that of the ONU does the ADC within the ONU continue to sample the analog input signal as usual. Otherwise, it switches to the standby mode to save energy until the timer expires. As shown in Fig. 1, there are N groups in OFDMA-PON and K ONUs within a group sharing a common destination. When an OFDM frame destined for Group₁ is broadcasted to all ONUs, only ONUs within Group₁ (green) keep working while others (red) are in the standby mode to save energy.

3 Experimental Setup and Results

To verify the feasibility of the proposed selective sampling receiver, we set up an experiment as shown in Fig. 2. In the OLT, the original data for two ONUs (ONU_{1-1} and ONU_{2-1}) in different groups are mapped through 16 QAM modulation format and then transferred to the time domain signals by 512 points IFFT. A cyclic prefix of 32 samples is used to eliminate inter-symbol interference. The Hermitian symmetry is applied to generate the real-valued OFDM signal. In the experiment, we use PN sequence to perform synchronization due to its good property of autocorrelation and high-synchronization accuracy.¹³ 4 PN sequences (PN_1 , PN_2 , PN_3 , and PN_4) are adopted and two headers (PN_1 - PN_2 - PN_3 - PN_4 and PN_1 - PN_2 - PN_3 - PN_3) for ONU_{1-1} and ONU_{2-1} are attached to the frame head, respectively.

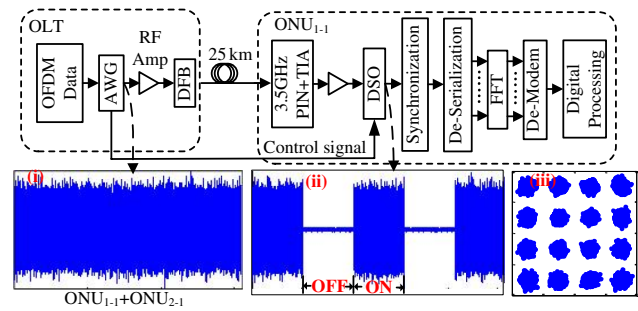


Fig. 2 Experimental setup of the proposed selective sampling receiver: insets (i) and (ii) are the transmitted and received waveforms, respectively; inset (iii) is the constellation.

Then, the OFDM data generated by MATLAB[®] are downloaded to the Tektronix AWG 7122C (Beaverton, Oregon), with 10-GSample/s sampling rate and 8-bit resolution. The bandwidth is 2.5 GHz and the raw bit rate is 10 Gb/s. The analog signal is applied to a directly modulated distributed feedback laser (DFB) laser biased at 60 mA. The output power of the DFB laser is ~ 8.7 dBm. After 25-km single-mode fiber transmission, the digital sampling oscilloscope with 10 GSamples/s is used to capture the signal for further DSP processing. The following operation includes synchronization, FFT, equalization, and so on. The sensitivity of the received signal is -26 dBm at the bit error rate (BER) of 3.8×10^{-3} .

In the experiment, since there is no real-time ONU receiver in our lab, we use AWG to switch on/off the ADC instead of the synchronization module. The transmitted waveform including two ONUs' data is shown in the inset (i) of Fig. 2. The received waveform of ONU_{1-1} under the condition of selective sampling is discontinuous, as shown in the inset (ii) of Fig. 2. The received samples for ONU_{1-1} can be demodulated correctly and the constellation is depicted in the inset (iii) of Fig. 2, which shows the feasibility of the proposed selective sampling ONU receiver.

Figure 3 gives the destination identification procedure and the results according to the different headers in the experiment. In the destination identification procedure shown in Fig. 3(a), cross-correlation is first performed between the receiving frame and PN_k ($k = 1, 2, 3, 4$). Then, the synchronization profile corresponding to each PN_k ($k = 1, 2, 3, 4$) is obtained in Figs. 3(b) and 3(c). According to the synchronization profile, the number of synchronization peaks and their corresponding positions are recorded for further destination identification. For example in Fig. 3(b), only one peak appears in each PN sequence and its position is different, meaning that the receiving frame contains the PN sequence PN_1 - PN_2 - PN_3 - PN_4 . That is, the destination of this frame is ONU_{1-1} since the detected PN sequences are consistent with the frame header of ONU_{1-1} in the experiment. Similarly, in Fig. 3(c), two peaks appear in PN_3 but no peaks appear in PN_4 , implying that the PN sequence PN_1 - PN_2 - PN_3 - PN_3 is included in the frame. It means that the destination of the receiving frame in Fig. 1(c) is ONU_{2-1} . From the results in Figs. 3(b) and 3(c), it can be clearly seen that the destination can be identified clearly. During the synchronization, if one of the synchronization peaks is missed, the start position of symbols can still be obtained with the help of other synchronization peaks. Nevertheless, the receiver

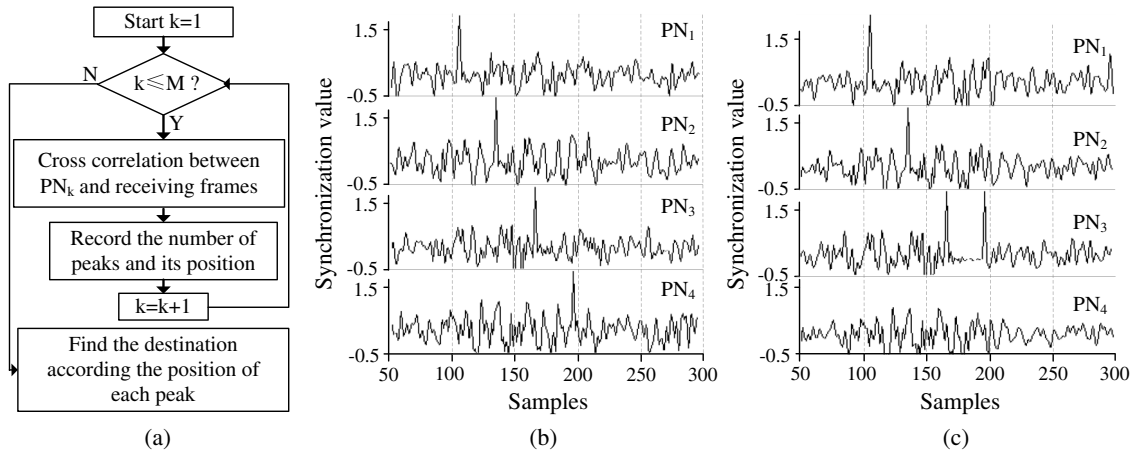


Fig. 3 Destination identification procedure (a) and the results under the receiving frame targeting to (b) ONU₁₋₁ and (c) ONU₂₋₁.

would make a mistake about the destination of this frame. Then, the control signal used to switch on/off ADC is generated according the destination of the receiving frame. For ONU₁₋₁, as long as the destination of the receiving frame is other ONUs, the ADC switches to standby mode until the timer expires. Otherwise, the receiving frame is being sampled and demodulated as usual.

4 Energy-Saving and Other Analysis

During the selective sampling procedure, the more time the ADC stays in standby mode, the more energy can be saved. However, the time spent on standby mode is significantly affected by the synchronization speed, because only after the destination of the receiving frame is identified, the ADC might switch to standby mode. Thus, it is desirable to reduce the length and the number of orthogonal PN sequences to accelerate synchronization. In fact, the number of PN sequences generated by primitive polynomials is limited, which is shown in Table 1. Moreover, only M^M different destinations can be identified through the arrangement of M orthogonal PN sequences. In the experiment, the coefficient of primitive polynomial is set to 5 and the length of PN sequence is 31 bits. Although the PN sequences added to the data stream increase the redundancy of the transmission, it has little impact on transmission efficiency because PN sequences are a small fraction of the OFDM frame.

In the energy analysis, we consider an OFDMA-PON system with 512 ONUs. When OLT broadcasts one OFDM

frame, the energy consumption of all ONUs using a conventional receiving method is denoted as E_t

$$E_t = NK(P_{\text{APD/TIA}} + P_{\text{LA}} + P_{\text{ADC}} + P_{\text{FFT}} + P_{\text{Digital}})T_{\text{Frame}}, \quad (1)$$

where N is the number of groups and K is the number of ONUs within a group. T_{Frame} is the length of an OFDM frame, which is 125 μs in this article. The power of APD/TIA, LA, ADC, FFT, and digital processing is denoted as $P_{\text{APD/TIA}}$, P_{LA} , P_{ADC} , P_{FFT} and P_{Digital} respectively, which has already been investigated in Ref. 11. The energy consumption of all ONUs using the selective sampling ONU receivers can be calculated as

$$E_s = NK(P_{\text{APD/TIA}} + P_{\text{LA}})T_{\text{Frame}} + (N-1)KP_{\text{ADC}}T_{\text{syn}} + K(P_{\text{ADC}} + P_{\text{FFT}} + P_{\text{Digital}})T_{\text{Frame}}. \quad (2)$$

T_{syn} is the time of synchronization and the ratio $T_{\text{syn}}/T_{\text{Frame}}$ is set to 0.1. This ratio is related with the synchronization time and the OFDM frame length. The synchronization time in traditional OFDM communication is on the order of microseconds.^{14,15} About the OFDM frame length, as the frame format for OFDM-PON has not been standardized yet, a 125- μs frame length is considered in our experiment, which is in accordance with gigabit-capable passive optical network (GPON) standards. The energy-saving efficiency η is also defined as follows

$$\eta = \frac{E_t - E_s}{E_t}. \quad (3)$$

The energy consumption and energy-saving efficiency with different numbers of groups N is shown in Fig. 4. We can see that an obvious reduction of energy consumption is obtained using proposed selective sampling receivers. Besides, the energy-saving efficiency increases with the number of groups N , since more ONUs can stay in standby mode with the increase of groups.

During the energy-efficient receiving method, only packets having a common destination can constitute a complete OFDM frame to be transmitted, therefore resulting in the packet delay. We study the delay performance for Poisson traffic using simulation. Consider a 10G OFDMA-PON

Table 1 Pseudorandom (PN) sequence design.

Coefficient of the primitive polynomial	Number of orthogonal PN sequences	Length of each PN sequence	Number of different destinations
3	2	$2^3 - 1$ bits	2^2
4	2	$2^4 - 1$ bits	2^2
5	6	$2^5 - 1$ bits	6^6
6	6	$2^6 - 1$ bits	6^6
7	18	$2^7 - 1$ bits	18^{18}

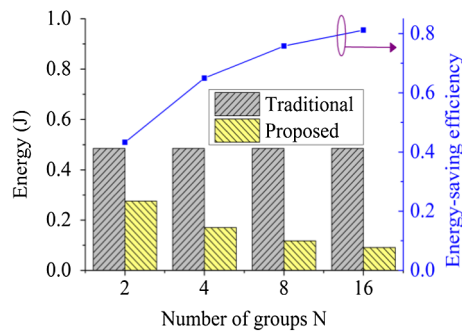


Fig. 4 Energy consumption and energy-saving efficiency with different number of groups N .

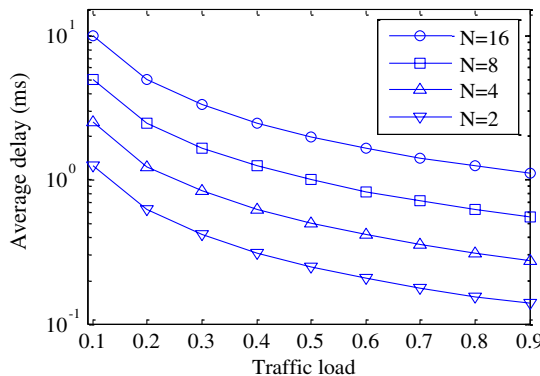


Fig. 5 Average delay versus traffic load under different number of groups N .

system supporting 512 ONUs. Figure 5 shows that the average delay first decreases with the increase of the traffic load. This is because with the increase of the traffic load, the packets sharing a common destination increase, and the time spent on constituting an OFDM frame decreases, therefore resulting in the decrease of the average delay. We can also see that the delay increases when the number of groups N increases. The increasing N results in the decrease of ONUs within a group owing to the fixed number of ONUs in the system, therefore resulting in the increase of average delay.

5 Conclusion

In this article, we proposed a physical-layer energy-efficient receiving method using a selective sampling receiver in OFDMA-PONs. The receiver only samples at the time when the incoming frame targets to the ONU and stays in standby during the rest of the time. An experiment is performed to verify its feasibility. The design of PN sequence and delay performance are also analyzed. The results show that using our proposed selective sampling receivers, ~60% energy can be saved when adopting four groups in OFDMA-PON with 512 ONUs.

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Weisheng Hu received his BS, MS, and PhD degrees from Tsinghua University, Beijing University of Science and Technology, and Nanjing University in 1986, 1989, and 1997, respectively. He joined Shanghai Jiao Tong University as a postdoctorate fellow from 1997 to 1998, and as a professor from 1999. He serves for four journals and 12 conferences, including IEEE JLT, OFC. His interests are on the optical transport network with GMPLS and optical packet switching.