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# Energy-efficient orthogonal frequency division multiplexing-based passive optical network based on adaptive sleep-mode control and dynamic bandwidth allocation

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**Abstract.** We propose an energy-efficient orthogonal frequency division multiplexing-based passive optical network (OFDM-PON) using adaptive sleep-mode control and dynamic bandwidth allocation. In this scheme, a bidirectional-centralized algorithm named the receiver and transmitter accurate sleep control and dynamic bandwidth allocation (RTASC-DBA), which has an overall bandwidth scheduling policy, is employed to enhance the energy efficiency of the OFDM-PON. The RTASC-DBA algorithm is used in an optical line terminal (OLT) to control the sleep mode of an optical network unit (ONU) sleep and guarantee the quality of service of different services of the OFDM-PON. The obtained results show that, by using the proposed scheme, the average power consumption of the ONU is reduced by ~40% when the normalized ONU load is less than 80%, compared with the average power consumption without using the proposed scheme. © 2016 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.OE.55.2.026108](https://doi.org/10.1117/1.OE.55.2.026108)]

Keywords: energy efficiency; quality of service; orthogonal frequency division multiplexing-based passive optical network; receiver and transmitter accurate sleep control and dynamic bandwidth allocation.

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## 1 Introduction

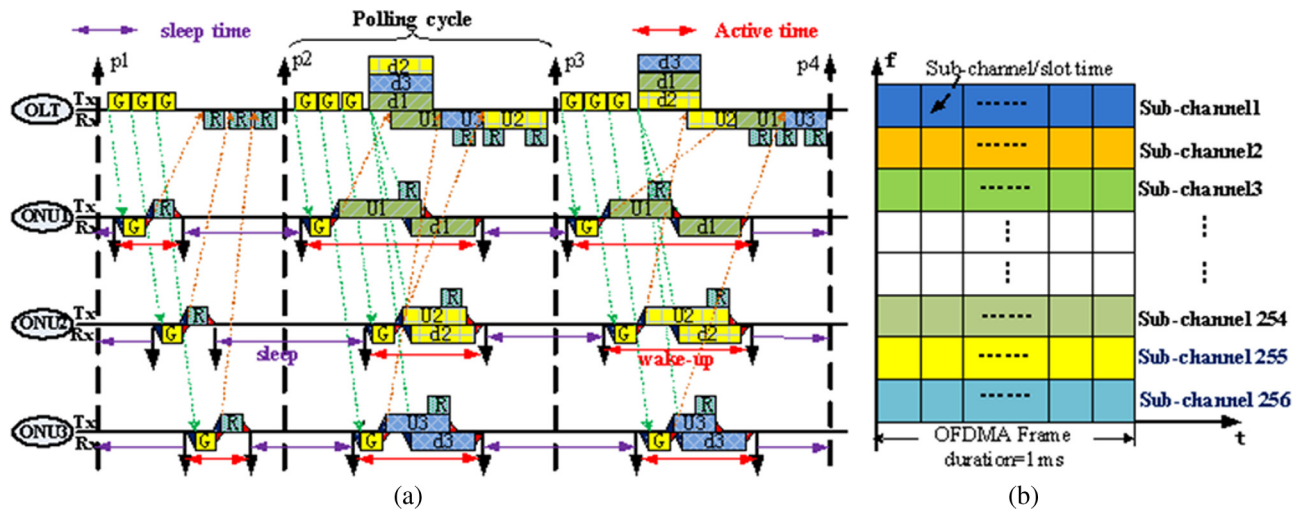
Recent studies have shown that the information technology industry of broadband communication networks has become one of the five highest energy consumption industries in the world. In particular, broadband access networks consume more than 70% of the energy of all communication networks.<sup>1,2</sup> Meanwhile, the orthogonal frequency division multiplexing-based optical access network (OFDM-PON) and metro-access network technologies have significant potential for many applications in next-generation broadband optical access networks because of their high spectral efficiency, strong robustness to chromatic dispersion, and great flexibility in dynamic bandwidth allocation.<sup>3,4</sup> However, OFDM-PON systems consume relatively more energy than other PON systems such as the time division multiple access-based passive optical network (TDMA-PON) and wavelength division multiplexing-based passive optical network (WDM-PON), since OFDM-PON employs more advanced digital signal processing (DSP) techniques than other PON systems.<sup>5</sup> Therefore, it is very important to design a suitable scheme to improve the energy efficiency of OFDM-PON systems.

So far, many schemes have been proposed to decrease the power/energy consumption of PONs and other communication systems. Some examples are optical network unit (ONU) sleep/doze methods<sup>6-9</sup> and other power/energy-saving methods of time-domain interleaved and selective sampling<sup>10-14</sup> for access networks and distributed dynamic clustering for long-term evolution heterogeneous networks.<sup>15</sup>

Wong et al.<sup>6</sup> numerically analyzed the power-saving effectiveness of a short cavity vertical cavity surface emitting laser (VCSEL)-based ONU over a distributed feedback-based ONU employing the various modes of operation of the WDM-PON and demonstrated an energy savings of up to 84% for a sleep mode. In Ref. 7, a just-in-time (JIT) dynamic bandwidth allocation (DBA) algorithm was designed to improve the energy efficiency of a 10-Gbit/s Ethernet PON (10G-EPON). In addition, different sleep mode mechanisms in an ONU and optical line terminal (OLT) for a point-to-point optical access network and TDMA-PON were investigated in Ref. 8. Additionally, Khotimsky et al.<sup>9</sup> proposed a parametric extension allowing a unified power management mode in which the ONU periodically turns off its receiver and transmitter in a cyclic sleep mode and performs infrequent bidirectional handshakes in a doze/sleep mode.

Recently, several power-saving schemes have also been proposed for optical OFDM-PON systems. For example, an energy- and cost-efficient WDM/OFDMA-based PON system, referred to as a NEWOPS, was proposed in Ref. 10. The NEWOPS not only has a high spectral efficiency and flexible subchannel bandwidth allocation but also solves the Rayleigh backscattering problem and achieves high energy and cost efficiency. Agmonet et al.<sup>11</sup> introduced a next-generation long-reach access optical network (with a 35-dB loss budget and 2-dB margin) delivering up to 40 G/40 G per passive 1:256 optical distribution networks, supporting a symmetrical 1 Gbit/s per user or up to 40 Gbit/s for business users. A physical-layer energy-efficient receiving

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**Fig. 1** (a) Timing diagram of energy-efficient RTASC-DBA program for OFDM-PON with sleep mode, active mode, and polling cycle, and (b) schematic diagram of an uplink channel allocation.

method based on selective sampling was utilized in Ref. 12 to realize an energy-efficient OFDM-PON system. Skubic et al.<sup>13</sup> addressed the energy consumption of different next-generation optical access solutions beyond 10G TDM-PON. In Ref. 14, a scheme was proposed to reduce the energy consumption of the ONUs by using a time-domain interleaved OFDM technique. Additionally, a physical-layer energy-efficient receiving method based on selective sampling in an OFDM-PON was reported in Ref. 12. However, these schemes obtain high energy efficiency only at the cost of a decrease in quality of service (QoS) and an overall increase in network cost. Moreover, the energy-efficient schemes in Refs. 7–9 and 13 cannot be directly applied to the OFDM-PON because these schemes cannot offer the preferred multiple subchannel scheduling in the frequency domain required by the OFDM-PON.<sup>16–21</sup> To the best of our knowledge, simultaneous energy consumption reduction and QoS guarantee have not yet been proposed in the literature.

In this paper, for the first time, we propose an energy-efficient OFDM-PON by using a bidirectional-centralized algorithm of receiver and transmitter accurate sleep control and dynamic bandwidth allocation (RTASC-DBA). The proposed scheme is an energy-efficient program implemented by a software method in which an OLT uses a cycle sleep mode combined with multicycle sleep mode to increase the sleep time of the ONU at its maximum limitation. Therefore, the energy consumption of an OFDM-PON using the RTASC-DBA can be significantly reduced, and meanwhile, the overall bandwidth scheduling policy of the RTASC-DBA algorithm can also guarantee the QoS of different priority services.

## 2 Principle of Energy-Efficient Receiver and Transmitter Accurate Sleep Control and Dynamic Bandwidth Allocation in Orthogonal Frequency Division Multiplexing-Based Optical Access Network

### 2.1 Timing Diagram of Energy-Efficient Program

The operation diagram for sleep mode, active mode, and polling cycle in an OFDM-PON using the RTASC-DBA

energy-efficient algorithm is shown in Fig. 1(a). Here, different colors represent different subcarriers occupied by different frames in the OFDM-PON, and the triangles represent the timers that are used to turn the transceiver on and off. Figure 1(b) shows the schematic diagram for the uplink channel allocation in the OFDM-PON with orthogonal frequency division multiple access (OFDMA) technology. Using this OFDMA, the uplink bandwidth resource is divided into a two-dimensional multiplexing model with a time slot and subcarrier. Compared with traditional PON systems that have only one slot dimension with regard to the granularity of bandwidth scheduling, the OFDMA technology greatly reduces the bandwidth granularity of the system.<sup>16</sup> In the OFDM-PON system with the OFDMA, each time slot/subcarrier can be dynamically allocated to different services of each ONU by the OLT. In the frequency domain, the OFDM carriers are divided into 256 groups, and 254 channels (channel no. 1 to channel no. 254) are used as the traffic load channels, while channels no. 255 and no. 256 are used as the control channels.

The functions of the REPORT and GATE frames in the proposed scheme are as follows: (1) The REPORT frame indicates the data cache size of each priority in the current ONU. It does not overlap in a time slot when sending the REPORT frame, but it overlaps in a time slot when sending the uplink data. (2) The GATE frame contains the precise sending and receiving times of up/downstream data for the corresponding ONU. Before the beginning of each RTASC-DBA cycle, the OLT receives all REPORT frames to achieve a dynamic bandwidth allocation. After that, the centralized OLT first sends a GATE frame, then sends the downstream data for each online ONU. Once it receives the GATE frame, the ONU can know the sending start time, the assigned length for the uplink data, the receiving start time, and the assigned length for the downstream data. Then the ONU sends the uplink data or receives the downstream data at the specified time slot. Finally, the ONU turns to a sleep mode for saving energy after finishing all data sending and receiving. While an ONU is active to receive the GATE frame at a right time, the fixed cycle bidirectional-centralized dynamic bandwidth allocation is employed in our work.

In this program, the GATE frame for the ONU with a larger bandwidth is sent first. When this ONU has received the GATE frame of the OFDM-PON, the ONU starts to send the uplink data. The ONU has two timers, which represent sending time of the uplink and the accepting time of the downlink, respectively. When the timer is coming, the ONU receives the downstream data from the OLT. After the uplink data are transmitted, the corresponding transmitter is closed. After processing the uplink and downlink data, the ONU sets to a deep-sleep timer and enters into a deep-sleep state. During the deep-sleep period, the ONU closes both its transmitter and receiver and only keeps the timing function, the user interface, and the uplink data cache. Meanwhile, the ONU can be active from the sleep mode and return to an active mode for receiving the GATE frame. This function is realized by the energy-efficient VCSEL ONU, which changes the state from sleep to activity or from activity to sleep during a polling cycle.<sup>7</sup>

## 2.2 Overall Process of Receiver and Transmitter Accurate Sleep Control and Dynamic Bandwidth Allocation Algorithm

The RTASC-DBA controls the total uplink and downlink bandwidth, the number of subcarriers, and the load of the ONUs. This arithmetic turns the variable polling cycle in a classic interleaved polling with adaptive cycle time algorithm<sup>22</sup> into a concentrated period with a fixed length. Therefore, the total uplink and downlink bandwidth of OFDM-PON is divided dynamically during the RTASC-DBA period without changing the load. In the centralized RTASC-DBA algorithm, the OLT authorizes each ONU in a centralized and unified mode. The start time and the end time of the uplink and downlink in a RTASC-DBA period are the same. The ONU dormancy is triggered by the OLT, and the overall process is as follows:

- Step 1 The OLT receives all of the ONU REPORT frames in the last RTASC-DBA cycle to acknowledge the priorities of all ONUs.
- Step 2 The OLT analyzes the priority queues from the REPORT frames and judges whether there is an ONU that enters into deep-sleep mode. Note that this process is equivalent to removing this ONU from the OFDM-PON logical topology.
- Step 3 The ONU has accumulated  $n$  (2 to 3) times for the conditions of  $REF=0$ ,  $RAF < RAF_{th}$ ,  $RBE < RBETH$ , and  $Cache < C_{th}$ , where  $REF$ ,  $RAF$ , and  $RBF$  are the bandwidth requirements of expedited forwarding (EF), assured forwarding (AF), and best effort (BE) services from each ONU of the OFDM-PON, respectively.  $REF_{th}$ ,  $RAF_{th}$ , and  $RBF_{th}$  are the threshold values of the EF, AF, and BE services, respectively. The cache is for downstream traffic, and  $C_{th}$  is the threshold value of downstream traffic. For the deep-sleep flag,  $C_{th}$  is set to 1; otherwise, it is set to 0. Then the dormancy intervals and the corresponding timers are set up. The OLT excludes the ONUs in the deep-sleep mode while distributing the bandwidth.
- Step 4 The OLT polls each ONU state at the start time of each RTASC-DBA to check whether there is a drop

of the ONU and to count the number of active ONUs.

- Step 5 After the above operations, the OLT successively calculates the length of the bandwidth allocation for each ONU uplink, according to the overall bandwidth scheduling policy proposed in this work.
- Step 6 The OLT successively calculates all receiving times and the lengths of bandwidth allocation for the downlink of each ONU, according to the downstream cache size and the forecasting condition.
- Step 7 The OLT calculates the total length of each ONU uplink bandwidth, then ranks the sending order of the ONUs from the largest to the smallest.
- Step 8 According to the order ranked in Step 7, the OLT first calculates the sending time of each ONU's uplink and downlink and marks them with the clock time. Then it assigns the upstream/downstream subcarriers for each ONU, judges whether each ONU is in sleep mode, and finally generates a GATE frame accordingly. Next, the OLT calculates the sending time of each GATE frame. At this time, the OLT finishes all calculations of the uplink and downlink bandwidth allocations in a RTASC-DBA period.

According to the uplink and downlink data flow, the ONU sleep mode is divided into two types: single-cycle dormancy or other multicycle dormancy. Regarding single-cycle dormancy, the ONU closes the optical transceiver, then enters into a dormant state. After the transceiver receives and sends the data, it will be active in the next cycle of RTASC-DBA. Then the optical receiver begins to monitor and receive the GATE frame from the OLT. For multicycle dormancy, the OLT assigns the ONU to enter into multicycle dormancy if the uplink and the downlink of the ONU are less than a certain threshold in multiple consecutive cycles. After receiving the GATE that carries the indication information of multicycle dormancy, the ONU enters into an active state directly, but continues to receive and send data in the current cycle. After that, it will turn to sleep mode. In such a case, the sleep time of the ONU is designated by the OLT. Generally, the sleep time is as long as several RTASC-DBA cycles (such as  $j$  cycles), and the ONU's sleep time is the start time of the  $j + 1$  RTASC-DBA cycle. Once the ONU is active, the receiver is opened to monitor and receive the GATE frame from the OLT. After the OLT sends all the GATE frames, the uplink and downlink will send and receive data according to the time assigned by the GATE frames.

## 3 Overall Bandwidth Scheduling Policy of Receiver and Transmitter Accurate Sleep Control and Dynamic Bandwidth Allocation in Orthogonal Frequency Division Multiplexing-Based Optical Access Network

In order to support multiple-service access and improve the efficiency of the energy savings of the OFDM-PON, the unified priority classification is further considered in the RTASC-DBA algorithm as EF, AF, or BE services.<sup>18</sup> The overall bandwidth scheduling policy of the RTASC-DBA algorithm for the OFDM-PON system is described in the following text. This algorithm periodically collects the bandwidth application information (all of the bandwidth application values carried by the REPORT frames) of each ONU of the OFDM-PON, which satisfies the conditions of bandwidth

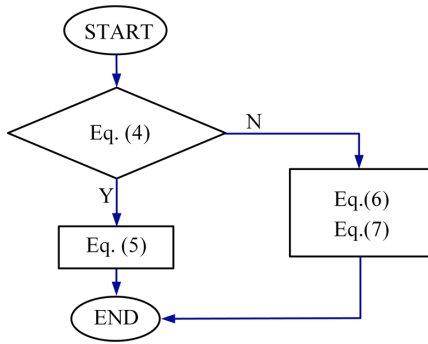


Fig. 2 Scheduling flowchart for different priorities of RTASC-DBA.

allocation and guarantees the QoS of different levels of access services with limited bandwidth resources. To achieve the scheduling policy of the OFDM-PON, first, in cycle  $i$ , the OLT identifies the bandwidth application values of different priority queues of each ONU, which can be denoted by matrix  $B$

$$B = \begin{bmatrix} B_{1,1} & \dots & B_{1,i} & \dots & B_{1,N} \\ B_{2,1} & \dots & B_{2,i} & \dots & B_{2,N} \\ B_{3,1} & \dots & B_{3,i} & \dots & B_{3,N} \end{bmatrix}, \quad (1)$$

where  $B_{1,i} (i = 1, 2, \dots, N)$ ,  $B_{2,i} (i = 1, 2, \dots, N)$ , and  $B_{3,i} (i = 1, 2, \dots, N)$  of matrix  $B$  are the bandwidth application values of the ONU EF, AF, and BE services, respectively.

After obtaining the bandwidth application information for different priority queues of each ONU in the OFDM-PON, the OLT carries out the overall bandwidth scheduling policy, as follows:

- Step 1 In order to be fair, the RTASC-DBA employs a priority balance factor  $k$  to perform the bandwidth allocation among different priorities, which first marks the system bandwidth of EF, AF, and BE services by using  $W_{EF}$ ,  $W_{AF}$ , and  $W_{BE}$ .
- Step 2 After finishing the bandwidth allocation among different priorities, the RTASC-DBA algorithm carries out the bandwidth scheduling policy within each priority.
  - a) When allocating bandwidth for the EF service, in order to guarantee the QoS of the OFDM-PON, the RTASC-DBA allocates the bandwidth for this type of service first, and the system meets its needs.
  - b) Then the RTASC-DBA allocates the bandwidth for the AF and BE services. This uses a bandwidth allocation algorithm with an optimal sleep efficiency (OSE) in order to achieve the best efficiency for the dormancy.

### 3.1 Bandwidth Scheduling Policy Between Priorities

After the OLT obtains the bandwidth request matrix  $B$  of cycle  $i$ , the total bandwidth scheduling is then carried out. The scheduling process in the OFDM-PON is shown in Fig. 2.

First, the system allocates the total bandwidth for the overall EF service. Because the EF service of the OFDM-PON is a high-priority service that needs to guarantee the

bandwidth, its bandwidth demand can be expected to have a high degree of stability. Then the RTASC-DBA completely meets the EF service application, as shown

$$W_{EF} = \sum_{i=1}^N B_{1,i}. \quad (2)$$

After completing the bandwidth allocation for the EF service, the RTASC-DBA adds up the values of the rest bandwidth  $W_{rest}$ , and  $W_{traffic}$  is the bandwidth of the overall service channel of OFDM-PON system. Then,

$$W_{rest} = W_{traffic} - W_{EF}. \quad (3)$$

Next, the RTASC-DBA carries out the bandwidth allocation between the priorities for AF and BE services. First, we calculate the number of the total bandwidth applications of AF and BE services. If  $W_{rest}$  completely meets the bandwidth demand of the AF and BE services, it can satisfy Eq. (4), as shown

$$\sum_{i=1}^N (B_{2,i} + B_{3,i}) \leq W_{rest}. \quad (4)$$

The bandwidth for each priority can be allocated by following Eq. (5):

$$\begin{cases} W_{AF} = \sum_{i=1}^N B_{2,i} \\ W_{BE} = \sum_{i=1}^N B_{3,i} \end{cases}. \quad (5)$$

If  $W_{rest}$  cannot meet the demand of the bandwidth for AF and BE services, Eq. (4) is not satisfied; that is, the value of the bandwidth application is higher than the rest of the OFDM-PON system bandwidth resources. In order to guarantee relative fairness between the priorities and prevent a priority from having excessive service, another priority service bandwidth is occupied. We then use the priority balance factor  $k$  for bandwidth allocation between AF and BE services. A specific distribution is shown in the following:

$$\begin{cases} W_{AF} = \left( \frac{\sum_{i=1}^N B_{2,i}}{\sum_{i=1}^N (B_{2,i} + B_{3,i})} + k \right) W_{rest} \\ W_{BE} = W_{rest} - W_{AF} \end{cases}, \quad (6)$$

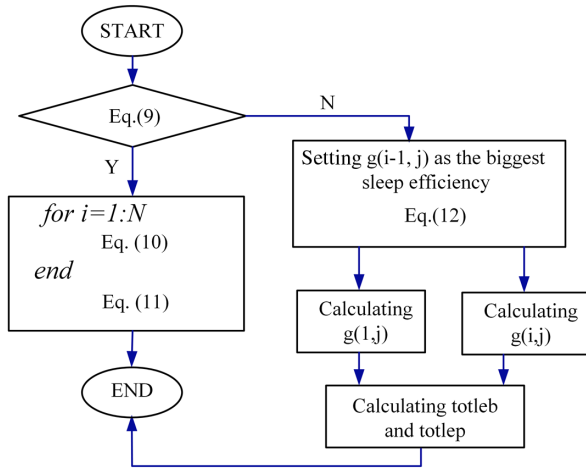
where  $k$  is determined by Eq. (7). The size of  $k$  can determine the size of the bandwidth for the AF service and guarantee the bandwidth requirements for the BE service

$$k \leq 1 - \frac{\sum_{i=1}^N B_{2,i}}{\sum_{i=1}^N (B_{2,i} + B_{3,i})}. \quad (7)$$

At this point, the RTASC-DBA of the OFDM-PON achieves a bandwidth allocation among different priorities, then  $W_{EF}$ ,  $W_{AF}$ , and  $W_{BE}$  are obtained.

### 3.2 Energy-Efficient Bandwidth Scheduling Policy Within Each Priority

For the energy-saving bandwidth allocation strategy of the EF service, the OLT meets the bandwidth requirement of the EF service owing to the bandwidth allocation between the priorities. Therefore, the bandwidth allocation within each



**Fig. 3** Bandwidth allocation flow diagram of each ONU AF service in OFDM-PON.

priority satisfies each ONU EF bandwidth requirement, as follows:

$$W_{1,i} = B_{1,i} (i = 1, 2, \dots, N). \quad (8)$$

For the energy-saving bandwidth allocation strategy of EF and BE services in the OFDM-PON, Fig. 3 shows the bandwidth allocation flow diagram for each ONU AF service. The RTASC-DBA has allocated the total bandwidth resources  $W_{AF}$  for AF service for the bandwidth allocation between different priorities. The RTASC-DBA can then allocate the total bandwidth  $W_{AF}$  to each ONU AF service.

The RTASC-DBA first performs a statistical analysis on the total bandwidth requirement of each ONU AF service, and compares it with  $W_{AF}$  to decide whether it meets each ONU requirement, as follows:

$$\sum_{i=1}^N B_{2,i} \leq W_{AF}. \quad (9)$$

If Eq. (9) is satisfied, it shows that  $W_{AF}$  meets the demand of the bandwidth for each ONU AF service. In addition, the RTASC-DBA process meets the bandwidth application of each ONU AF service. This is expressed as follows:

$$W_{2,i} = B_{2,i} (i = 1, 2, \dots, N). \quad (10)$$

After finishing the bandwidth allocation for the AF service, the rest of the bandwidth merges into the BE bandwidth, as shown in the following:

$$W_{BE} = W_{BE} + \left( W_{AF} - \sum_{i=1}^N W_{2,i} \right). \quad (11)$$

Otherwise, Eq. (9) shows that  $W_{AF}$  cannot completely meet the demand of the bandwidth for each ONU AF service.

To guarantee the effectiveness of the energy-saving bandwidth allocation algorithm, each ONU has the best sleep efficiency. We then put forward a type of bandwidth allocation algorithm within the priorities. This algorithm uses a sleep efficiency factor  $P(i)$  according to a dynamic programming design to achieve the best effect of dormancy.  $P(i)$  can be expressed as

$$P(i) = \frac{B_{2,i}}{\sum_{i=1}^N B_{2,i}}. \quad (12)$$

We assume that  $g(i, j)$  is the biggest sleep efficiency value, and  $j$  is the total residual bandwidth value that can be available for current allocation. When the serial number of the ONU can meet the requirement of bandwidth allocation numbered by  $1, 2, \dots, i$  and  $0 \leq j \leq B_{2,i}$ ,  $B_{2,i}$  cannot obtain the required bandwidth; when  $j \geq B_{2,i}$ , the options are as follows:

1. Not allocating the bandwidth for  $B_{2,i}$ . The biggest sleep efficiency is then  $g(I-1, j)$ .
2. Allocating the bandwidth for  $B_{2,i}$ . Then there is a sleep efficiency  $P(i)$ , and the rest of the bandwidth is  $j - W_{2,i}$ . The bandwidth is allocated to  $B_{2,1} B_{2,2} \dots B_{2,i-1}$  simultaneously. The biggest sleep efficiency is  $g[I-1, j - W_{2,i} + P(i)]$ .

The expected maximum sleep efficiency is the larger of the two. Therefore, a recursive formula can be

$$g(i, j) = \begin{cases} g(i-1, j) & 0 \leq j \leq B_{2,i} \\ \max\{g(i-1, j), g[i-1, j - W_{2,i} + P(i)]\} & j \geq B_{2,i} \end{cases}. \quad (13)$$

The boundary values of the algorithm are

$$g(1, j) = P(1), \quad j \geq B_{2,1}, \quad (14)$$

$$g(1, j) = 0, \quad j < B_{2,1}. \quad (15)$$

The calculation program of  $g(1, j)$  can be as follows:

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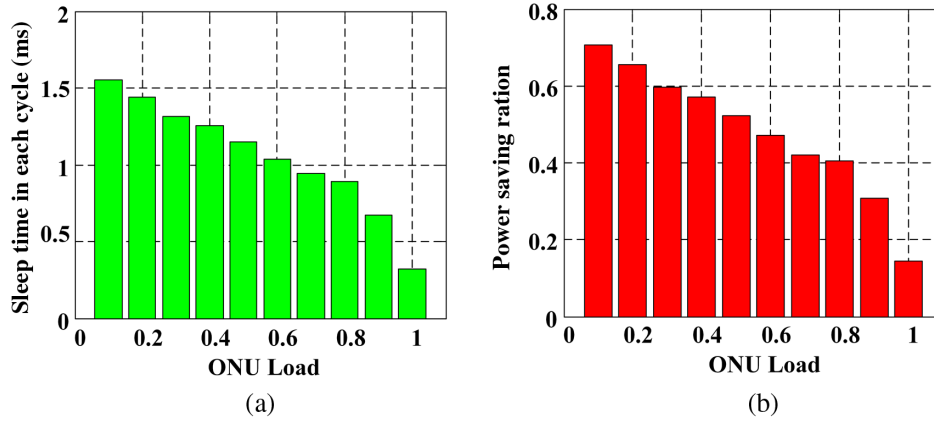
for j = 0: WAF
    if(j ≥ B2,1);
        g(1, j) = p(1)
    else
        g(1, j) = 0.
    
```

The calculation program of  $g(i, j)$  can be as follows:

```

for i = 2:n
    for j = 0: WAF
        if(j ≥ B2,i & &
            g(i-1, j) ≤ g(i-1, j - B2,i) + p(i))
            g(i, j) = g(i-1, j - B2,i) + p(i)
        else
            g(i, j) = g(i-1, j).
        
```

For the bandwidth allocation algorithm within the priorities, the algorithm has the OSE when an ONU AF bandwidth requirement is  $B_{2,i}$ . In addition, the algorithm either



**Fig. 4** (a) Relationship of ONU sleep time and ONU load in each OFDM-PON polling cycle, and (b) relationship of energy-saving ratio and ONU load.

satisfies its requirement or does not satisfy its requirement. That is, for  $x_i \in \{0,1\}$ , the allocation algorithm for sleep efficiency can be expressed as  $\sum_{i=1}^n x_i p(i)$ . The ultimate goal of the bandwidth allocation algorithm with OSE is to obtain the biggest sleep efficiency  $\sum_{i=1}^n x_i p(i)$ .

The calculation program for obtaining OSE can be as follows:

for ( $totlep = 0, totleb = 0, i = n; i \geq 2; i--$ )

if ( $g(i, restb) > g(i-1, restb)$ )

$restb- = B_{2,i}, totleb+ = B_{2,i},$

$totlep+ = p(i), W_{2,i} = B_{2,i};$

else  $W_{2,i} = 0;$

if ( $g(n, W_{AF}) - totlep = p(1)$ )

$totleb+ = B_{2,i}, totlep+ = p(i),$

where  $totlep$  is the obtained OSE,  $totleb$  is the total allocated bandwidth value, and  $restb$  is the current number of remaining bandwidths.

Using the bandwidth allocation algorithm, the bandwidth allocation of AF service  $W_{2,i}$  can be obtained. The BE service bandwidth allocation mode is the same as that of the AF service, which gets the allocated bandwidth of  $W_{3,i}$ . The bandwidth scheduling of OFDM-PON has been completed, and the result matrix for the bandwidth allocation is shown in Eq. (16):

$$W = \begin{bmatrix} W_{1,1} & \dots & W_{1,i} & \dots & W_{1,N} \\ W_{2,1} & \dots & W_{2,i} & \dots & W_{2,N} \\ W_{3,1} & \dots & W_{3,i} & \dots & W_{3,N} \end{bmatrix}. \quad (16)$$

Finally, every value of this matrix  $W$  is written into the corresponding field of the GATE frame of each ONU.

## 4 Results and Discussion

### 4.1 Setting of the Key Parameters

An OFDM-PON simulation platform is set up to verify the effectiveness of the proposed energy-efficient scheme. The parameters are given as follows: (1) the OFDM-PON system is composed of one OLT and 64 ONUs, and the optical fiber transmission distance between the OLT and ONUs is 40 km.<sup>5</sup>

(2) The processing time for a GRANT frame or REPORT frame is assumed to be  $0.5 \mu\text{s}$ .<sup>20</sup> (3) The rates for both upstream and downstream are 10 Gbit/s. (4) The subcarriers of the OFDM are divided into 64 groups in the frequency domain. Note that the method of the interface control information binding remote terminal is used for the transmission of authorized frames, regardless of the occupation situation of subcarriers. (5) In the time domain, the OFDM-PON system adopts a method of periodic polling for multiplexing, and the fixed polling cycle of its RTASC-DBA algorithm is 2 ms. (6) The buffer memory of the EF queue is 2 MB, the buffer memory of the AF queue is 3 MB, and the buffer memory of the BE queue is 5 MB for the ONU. Additionally, the buffer memory allocated for downlink data is 5 MB for the OLT. (7) The data used by the OLT and ONU are self-similar flow, which is superimposed by multiple ON/OFF sources. Each ONU has the same set of parameters, but the packet size and the interpacket intervals vary with different services of the OFDM-PON. The packet size of the EF service is a fixed length of 64 bytes; the EF service mainly simulates a voice-packet service. The packet sizes of the AF and BE services obey a uniform distribution of 64 to 1518 bytes. The AF simulates an FTP/HTTP service, and the BE simulates an MPEG video service. In addition, there are 20% of EF, 35% of AF, and 45% of BE services in the total services of each ONU, and the values of the service loads range from 0.1 to 1.

### 4.2 Analysis of Energy-Saving Efficiency

Figure 4(a) shows the ONU average sleep time in each polling cycle (where the polling cycle is 2 ms) using the RTASC-DBA energy-efficient algorithm of the OFDM-PON system in different loads. We can see that when the loads increase, the ONU dormancy time is gradually reduced. When the ONU load is less than 0.8, the sleep time is longer than 0.85 ms. For 2-ms polling cycles, the sleep time has a high level. Figure 4(b) shows the average energy-saving ratio of the OFDM-PON considering the power and the average sleep time of the ONU in active and sleep modes.  $E_1$  refers to the consuming energy of the ONU when the dormancy mechanism is employed in the process of simulation, as follows:

$$P_{\text{sleep}} = 9\% \times P_{\text{active}}, \quad (17)$$

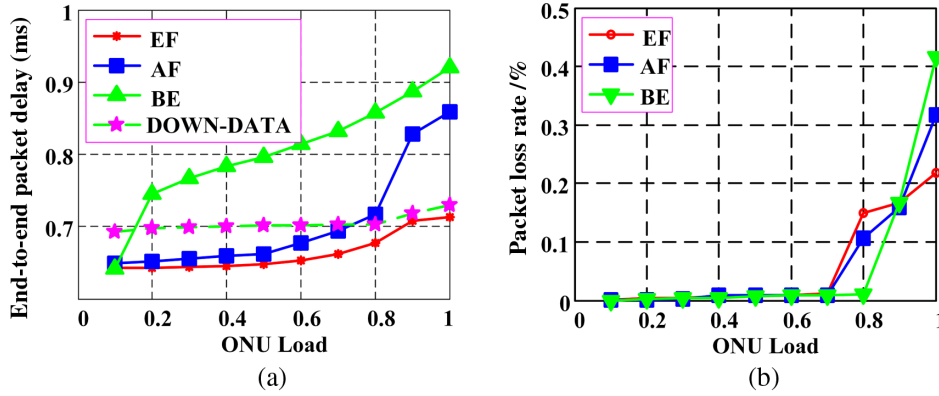


Fig. 5 (a) Relationship of up/downlink data packet end-to-end delay and ONU load, and (b) packet loss rate of three different priority services of OFDM-PON.

$$\eta = 1 - \frac{E_1}{E_2} \times 100\%, \quad (18)$$

$$E_1 = \sum_{i=1}^N (T_{\text{active}}^i \times P_{\text{active}} + T_{\text{sleep}}^i \times P_{\text{sleep}}). \quad (19)$$

The total  $E_2$  refers to the energy that the ONU consumes when the dormancy mechanism is not employed in the time interval of the simulation

$$E_2 = N \times (T_{\text{active}} + T_{\text{sleep}}) \times P_{\text{active}}. \quad (20)$$

The average sleep time  $T_{\text{sleep}}$  refers to, under a certain load, the average sleep time of each ONU that is active in this simulation.  $T_{\text{active}}$  is the active time when the ONU transceiver of the OFDM-PON is normally active. Therefore, the average energy-saving rate  $\eta$  of the OFDM-PON refers to, under a certain load, each ONU average energy-saving rate. The operating power  $P_{\text{active}}$  refers to the power that the ONU uses in the normal mode, and the dormant power  $P_{\text{doze}}$  refers to the power that the ONU uses in a dormant mode. The dormant power is 9% of the operating power.<sup>20</sup> From Fig. 4(b), we find that the energy-saving ratio has decreased as the load increases, but the energy-saving efficiency is quite significant for the case of low load. When the ONU load of the OFDM-PON is less than 0.8, the average energy-saving rate is higher than 40%. In order to guarantee

the performance of the energy-saving OFDM-PON, we consider avoiding a deterioration in QoS owing to energy savings. For example, we set the balance factor in the OSE overall bandwidth scheduling policy.

Figure 5(a) shows that the end-to-end delay of the uplink/downlink packets changes with different ONU loads in the OFDM-PON. Figure 5(b) shows that the packet loss rate of different priority services varies with changes in the ONU load. Note that the end-to-end packet delay refers to the time period from sending the packet to receiving the packet, including the propagation delay and the delay of restoration from sleep. From the results shown in Figs. 5(a) and 5(b), we can see that the downstream data delays and the various businesses' upstream data delays are less than 0.95 ms for the case of a full load. This completely meets the suggestion for the time delay of data service in IEEE802.1D. In addition, the end-to-end packet delay of EF service is minimal, and then is that of the AF service. The end-to-end packet delay of the BE service is the longest, and this meets the actual demand of high-priority service to guarantee a high quality of data transmission. There is no adjustment for the downstream data load during the simulation process, and the entire downlink end-to-end packet delay does not change much, maintaining a value of approximately 0.7 ms. However, the downlink packet delay increases when the upstream data load is full. In Fig. 5(b), the packet loss rate of three different priorities is almost zero when the ONU load is below 0.7. Above 0.8 of the load, the packet loss increases

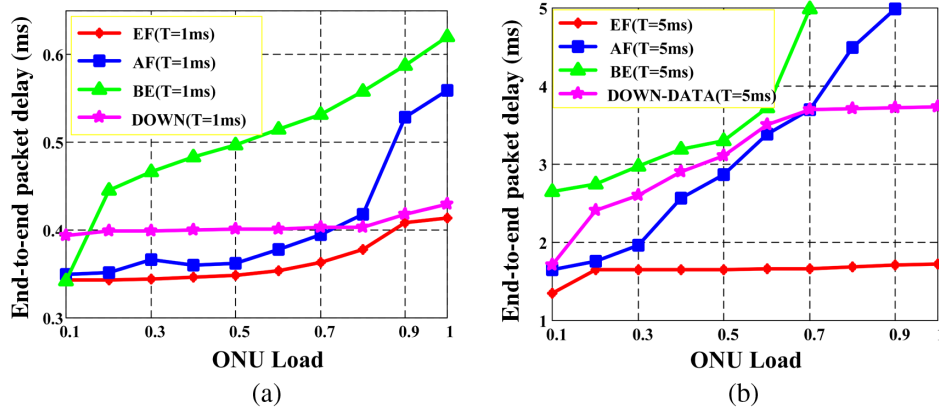


Fig. 6 (a) Relationship of up/downlink data packet end-to-end delay and ONU load with 1-ms polling cycle, and (b) relationship of packet end-to-end delay and ONU load with 5-ms polling cycle.

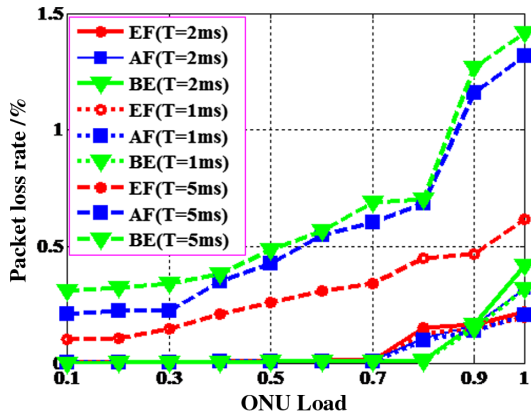


Fig. 7 Packet loss rate in OFDM-PON for different polling cycles.

significantly; however, it still remains at a very low level (less than 0.45%, even at a full load).

In addition, polling cycle  $T$  also affects the performance of the energy-efficient system, including the end-to-end packet delay and the packet loss rate. Thus, we must look for the most appropriate polling cycle. In the simulation,

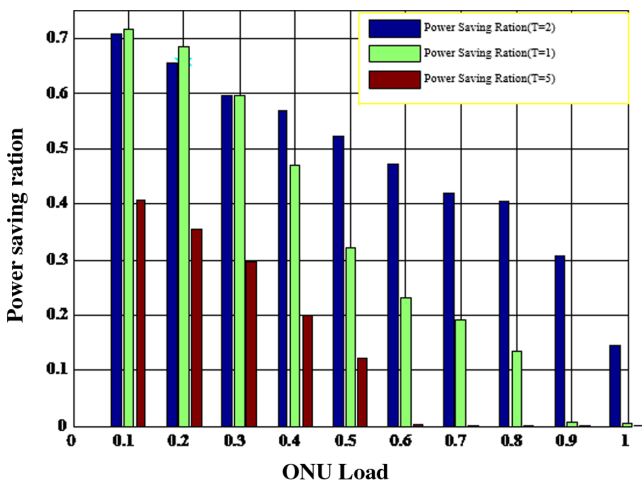


Fig. 8 Energy-saving ratio and ONU load in OFDM-PON for different polling cycles.

three different  $T$  values of 1, 2, and 3 ms are set. Figure 6 shows that the end-to-end delay of the uplink/downlink packets changes with different ONU loads for polling cycles of 1 and 5 ms. From the results shown in Fig. 6, we can see that the end-to-end delay of the 1-ms polling cycle is lower than that of the 2-ms polling cycle. This is just the opposite of the 5-ms polling cycle. In the case of the 5-ms polling cycle, the end-to-end pack delays of the AF and BE services dramatically increase when the ONU load is 0.5 because the low-priority services cannot be transmitted in time.

In Fig. 7, the packet loss rate of the 1-ms polling cycle is close to that of the 2-ms polling cycle, and the former has less packet-loss probability. However, the packet loss rate of the 5-ms polling cycle is very high. The overflowed packets must be discarded because of the limited buffer, which seriously affects the QoS of the OFDM-PON. Therefore, the 5-ms polling cycle cannot be employed. The 1-ms polling cycle can guarantee a better QoS for its low end-to-end packet delay and packet loss rate.

Figure 8 shows the reasons for doing so. In the case of the 1-ms polling cycle, the average energy-saving ratio is very high when the ONU load is less than 0.5, but it decreases quickly when the ONU load is more than 0.6. Finally, it becomes zero at a full load. Therefore, if the polling cycle is much smaller and the load is much higher, the ONU transceivers must always be turned on, thus a high energy-saving efficiency cannot be achieved.

All of the above analytical results indicate that the 2-ms polling cycle is a good choice. Figure 9(a) shows the influence that the packet loss rate and the loads have on the energy savings of the OFDM-PON system for the case of the 2-ms polling cycle. Figure 9(b) shows the percentage of energy savings of the 2-ms polling cycle as well as the other energy-saving methods, and as a function of network load.

Considering the uplink total packet-loss rate and the ONU load, Fig. 9(a) shows that 0.6 to 0.7 of the loads can have the best efficiency. Under the circumstances, both the entire network QoS and the energy-saving efficiency of the OFDM-PON are acceptable. However, when the load is higher than the scope of 0.6 to 0.7, the packet loss rate and the packet delay of service are relatively high, and thus are not conducive to the performance of the entire OFDM-PON. There

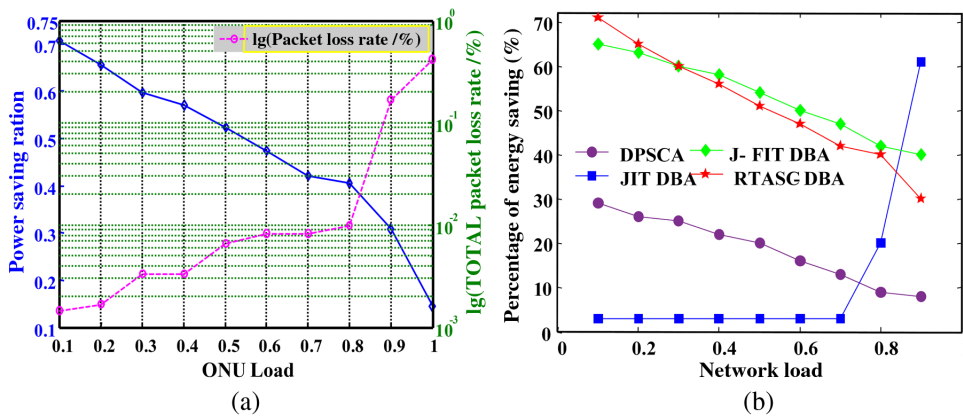


Fig. 9 (a) Relationship of ONU load-uplink packet loss rate, load, and energy saving percentage in OFDM-PON, and (b) percentage of energy savings of different energy-saving methods. DPSCA, dynamic power consumption state adaptation scheme; JIT DBA, just-in-time with varying-polling-cycle-time DBA scheme; J-FIT DBA, just-in-time with fixed-polling-cycle-time DBA scheme.

exists a waste of bandwidth since the bandwidth utilization rate of the OFDM-PON is not high when the load is less than the scope. As shown in Fig. 9(b), the dynamic power consumption state adaptation (DPCSA) scheme, which uses an adjustable modular DSP design for the OFDMA-PON, can offer up to 30% less consumption at a 0.1 load and 0.7 DPCSA threshold.<sup>5</sup> However, it is important to note that the energy-saving ratio is less than 20% for loads close to 0.5. Both the JIT with varying polling cycle times and JIT with fixed polling cycle times (J-FIT) DBA algorithms result in improved energy efficiency for a 10G-EPON system,<sup>7</sup> and the J-FIT algorithm performs better than the JIT algorithm at low network loads. Unfortunately, the J-FIT DBA leads to an increased average delay. Compared with these energy-saving methods, a percentage of energy savings of up to 70% could be achieved at a 0.1 load and 2-ms polling cycle for the proposed RTASC-DBA algorithm. Moreover, the RTASC-DBA algorithm is able to sustain power savings at levels of more than 40% even for loads that are over 0.6.

## 5 Conclusions

In this paper, an RTASC-DBA algorithm for an OFDM-PON has been proposed and verified to improve the energy efficiency of an OFDM-PON system. This scheme can successfully save energy and meet the requirements of packet loss rate and delay under different loads. The obtained results show that loads in the range of 0.6 to 0.7 can achieve the best efficiency. Under the circumstances, both the entire network QoS and the energy-saving efficiency of the OFDM-PON are acceptable. Therefore, the proposed scheme is very promising for future QoS-aware energy-efficient OFDMA-PONs.

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