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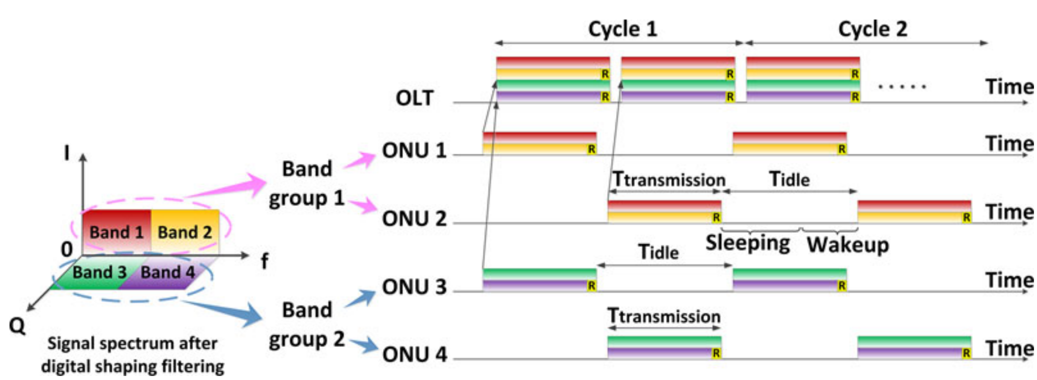

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Energy-Efficient Scheme Based on Sub-Band Grouping and Allocating for Digital Filter Multiple Access Adopted PON

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Abstract: An energy-efficient optical access network scheme based on sub-band grouping and allocating is proposed and studied for the digital filter multiple access adopted passive optical network (DFMA-PON). In this scheme, sub-bands generated in digital sdomain are grouped as band groups and properly allocated for optical network unit (ONU) transmissions to reduce the transmission time. Based on this, longer sleeping time can be provided to each ONU, and some more energy can be saved. Numerical evaluations indicate that comparing with basic DFMA-PON, significant energy is saved by the proposed scheme, and a promoted energy saving performance can be achieved by properly arranging the number of sub-bands assigned in a band group. Furthermore, the technology improvement and its impact on the performance of the scheme are also investigated. It is demonstrated that comparing with the conventional network, the proposed scheme possesses prominent energy saving potential. It can be considered as a potential solution for future energy-efficient optical access network.

Index Terms: Access network, digital filer multiple access (DFMA), energy efficiency, passive optical network (PON).

1. Introduction

The rapid development of information technology industry in recent years brings in exponential growth of energy consumption to telecommunication networks. In a general telecommunication network, its power consumption is contributed by thousands of active components scattering all over the network. Nevertheless, most of the power is consumed in the access network segment, since that it contains the largest quantity of network elements and provides various network services [1]. As a result, reducing the energy consumption of access network, especially the most widely employed optical access network (OAN), is an effective way to solve the energy efficiency issue for telecommunication network.

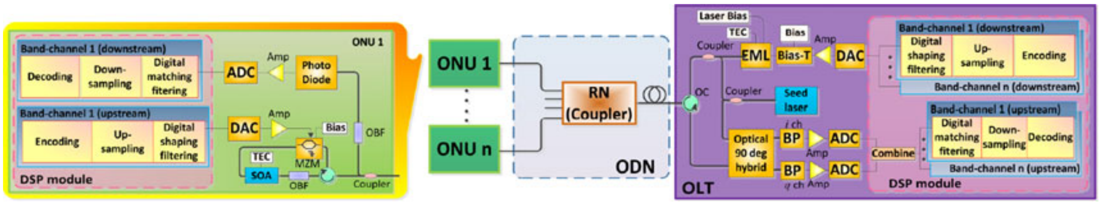

Fig. 1. Schematic of a DFMA-PON (OC: optical circulator; BP: balanced photodetector).

For the past few years, a vast number of literatures have been reported on the topic of reducing the energy consumption of OAN. Most of these reports concerns on network transport [2]–[4], photoelectric transducer [5], multi-mode component [6], [7], resource scheduling [8]–[10], signal procedure [11], etc. With the booming of user demands, further enhancement on energy efficiency is becoming increasingly essential to next generation OAN. Therefore, advanced energy-efficient resource scheduling scheme is proposed for the time and wavelength division multiplexed passive optical network (TWDM-PON) [12]. However, its energy saving potential is limited by the fundamental of TWDM-PON, which is the integration of time division multiplexing (TDM) and wavelength division multiplexing (WDM). Moreover, the fact of single tunable transceiver deploying at the optical network unit (ONU) side restricts the flexibility of resource scheduling on wavelength level since it is not a fast process for an ONU to convert its wavelength. Besides the TWDM-PON, the scheme of digital filter multiple access adopted passive optical network (DFMA-PON) is also a good candidate for the next generation OAN [13]–[15]. It offers multiple accesses on spectral overlapped orthogonal sub-band level by introducing the digital-filtering-associated technique into digital signal processor-based optical transceivers, and possesses the adaptability to software-defined network. Based on this technology, the DFMA-PON shows prominent characteristics of high operation flexibility and high spectrum efficiency potential, and its great operability for signal processing and resource scheduling on sub-band level provides enormous potential in further improving the energy efficiency of next generation OAN. Nevertheless, up to present, the energy saving potential of the DFMA-PON has hardly been considered. Its deployment prospection and cooperation with modern access technologies for further energy saving are rarely investigated.

In this paper, we creatively propose an energy-efficient scheme termed as time division multiple band allocation passive optical network (TDMBA-PON) for DFMA-PON based on sub-band grouping and TDM techniques. It is performed through grouping a number of sub-bands generated by digital filtering technique as a band group, and instructing multiple ONUs to share the band group by time division mode. The performance of the scheme is evaluated in both scientific and practical views. The numerical results indicate that the scheme effectively saves energy, and it has prominent practical prospect. The paper is organized as follow. Section 2 introduces the theory of DFMA-PON technique and presents a thorough theoretical analysis of the proposed TDMBA-PON. Detailed numerical investigations and comparisons are given in Section 3. Finally, a brief conclusion is presented in Section 4.

2. Principles and Theoretical Analysis

The basic architecture of a DFMA-PON is shown in Fig. 1 [13]. It is similar to a conventional passive optical network (PON) with the configuration that ONUs and optical line terminal (OLT) are connected via a passive optical distribution network (ODN). A digital processing module is deployed in each ONU and OLT. Similar to the structure reported in [16], to deal with the optical beat interference issue, coherent detection and seed laser are adopted at OLT side, and the seed laser is distributed to every ONU for their upstream transmissions.

During upstream transmission, an ONU firstly encodes its data, and then L additional zeros are inserted into every two adjacent data samples for up-sampling (up-sampling factor: $L+1$). After the up-sampling, a digital shaping filtering operation is done. The impulse response of the digital shaping filter, are confirmed by selecting phase (I or Q) and setting central frequency f_c, which are defined as

$$h(t) = \begin{cases} s(t)\cos(2\pi f_c t) \ (\mathrm{I-phase}) \\ s(t)\sin(2\pi f_c t) \ \ (\mathrm{Q-phase}) \end{cases} \tag{1}$$

where

$$s(t) = \frac{\sin\left[\frac{\pi(1-\delta)tf_{DAC}}{L}\right] + \left(\frac{4\delta t f_{DAC}}{L}\right)\cos\left[\frac{\pi(1+\delta)tf_{DAC}}{L}\right]}{\pi t\left[1-\left(\frac{4\delta f_{DAC}}{L}\right)^2\right]\frac{f_{DAC}}{L}}. \tag{2}$$

In (2), the factor δ controls the excess bandwidth of the filter, while f_{DAC} refers to the sampling rate of the digital-to-analog-convertor (DAC) that the ONU employs. The central frequencies are written as

$$f_c = \frac{(2b-1)f_{DAC}}{(2L+2)} \qquad b \in (1, 2, 3, \ldots), b \leq \frac{(L+1)}{2}. \tag{3}$$

These processes are accomplished by the digital signal processing (DSP) module. After that then, a DAC, a radio frequency amplifier, and a single-drive Mach-Zehnder modulator (MZM) are adopted to modulate signals into the upstream light wave. This light wave comes from the seed laser located at the OLT side and is amplified by semiconductor optical amplifier (SOA) before being modulated. Next, being converged with other optical signals from other ONUs at the remote node (RN), the optical signals are transmitted to the OLT. At the OLT end, a coherent detector, two radio frequency amplifiers, and two analog-to-digital-convertors (ADCs) jointly transfer the signals from the optical domain to digital domain, and then forward them to the digital processing module. The DSP module would combine these signals, and according to the phase and f_c parameters that the ONU adopts in the shaping filtering process, the DSP module in the OLT sets up a matching filter with impulse response $g(t) = h(-t)$ in correspondence, to extract signals. Finally, after a down-sampling process that eliminates the additional data samples, the data can be recovered by a decoder. Here, it should be mentioned that the sampling rates of DAC and ADC are set to be identical.

The transmission in downstream direction happens on a different optical wavelength. According to the destined ONU, downstream data is encoded, up-sampled, and processed by specified digital shaping filters. After digital shaping filtering, all the downstream signals are converged before successively passing through a DAC and a radio frequency amplifier, and then the signals would be modulated into downstream light wave by an electro-absorption modulated laser (EML). At ONU side, the downstream optical signals go through an optical coupler and an optical bandpass filter (OBF) before being received by photo diode. Then, after jointly transferred the signals to digital domain by photo diode, radio frequency amplifier, and DAC, the ONU could recover its downstream data via setting up corresponding digital matching filter and going through down-sampling and decoding processes.

In each transmission direction of this PON system, each pair of digital shaping filter and matching filter establishes a sub-band-channel (refer as “band” in the rest of the paper) in digital domain for data transmission. Therefore, multiple bands are set up by employing different combinations of phase parameter and central frequency parameter for different pairs of digital shaping filter and matching filter, and each band occupies an individual bandwidth. Hence, in each transmission direction, ONUs can exchange data with the OLT simultaneously through a single wavelength by utilizing different bands, and collision and interference are avoided. Here, it should be mentioned that since different propagation delays of different ONUs would affect the orthogonality of signals in I and Q phases and result cross-talk between different bands in upstream transmission, propagation delay difference should be eliminated or compensated for the purpose of ensuring relevant signals from different ONUs could arrive at OLT at a same time. In this paper, since we focus on providing an energy saving scheme for DFMA-PON, this cross-talk effect is not discussed, and we adopt identical propagation delay for different ONUs to deal with this effect. In the DFMA-PON, a DSP module can simultaneously manage the processing of multiple bands. Therefore, if more bands are occupied by an ONU, the corresponding bandwidth of this ONU is increased, then less time is spent to transmit a same amount of data, and longer spare time is obtained for this ONU. During the spare time, the ONU can turn into power saving mode to save energy, and other ONUs could occupy the bands to accelerate their transmissions. Consequently, the band grouping and TDM integrated TDMBA-PON is proposed and studied to promote energy efficiency for DFMA-PON.

In this paper, we take a TDMBA-PON with n ONUs that have equal load in both directions for instance. All ONUs use a same wavelength for transmissions in a same direction. Although advanced modulation formats such as PAM4 is applicable to the TDMBA-PON, simple modulation format of on-off keying is adopted in our investigation for the sake of convenience and modulation format consistency in results comparison. In upstream direction, $k-1$ ($k \geq n$) zeros are inserted into every two adjacent data samples for up-sampling. Correspondingly, k bands are able to be established in digital domain by the digital filtering technique, and each band has a bandwidth of $C_{band} = f_{DAC/ADC}/k$, where $f_{DAC/ADC}$ stands for the sampling rate of DAC/ADC. Assuming m ($1 \leq m \leq k$) bands are assigned as a band group, then k bands are divided into $\{k/m\}$ band groups, and each band group serves $\{nm/k\}$ ONUs. Here, the operation $\{x\}$ denotes calculating the smallest integer greater than or equal to x. During transmission, a band group allocates all its bands to an ONU when it is serving the ONU. Correspondingly, the ONU constructs m shaping filters in its DSP module with m different I/Q and f_c set pairs, and delivers its data by simultaneously using the m allocated bands. Hence, if an amount of data *Data* is piled in an ONU during the observation time $T_{observe}$, the needed transmission time is calculated as $T_{transmission} = Data/(mC_{band})$, which is m times shorter than the time that is required by using one band for transmission. Consequently, the idle time of this ONU in upstream direction can be written as

$$T_{idle} = T_{observe} - T_{transmission}. \tag{4}$$

Similarly, in downstream direction, k-1 zeros are inserted into every two adjacent data samples and m bands are grouped as a band group as well. In this way, the downstream transmission bandwidth of an ONU is same as that in upstream direction, and upstream and downstream transmissions of an ONU do coincide. Regarding the cycle time T_{cycle} that all the $\{nm/k\}$ ONUs are served once as the observation time, the available sleeping time of each ONU can be deduced as

$$T_{sleeping} = T_{cycle} - T_{transmission} - \alpha \tag{5}$$

where α refers to the sum of the sleep-to-active status transition time, the transmission gap time, and the digital filtering processing delay time.

In our scheme, gate and report messages are used as well to deliver information such as the allocated transmission time, sleeping time, idle time, and required transmission time for each ONU. In the downstream direction, each band group determines a band to deliver gate messages. When a band group is delivering downstream signals to an ONU, this gate-delivering band sends the gate message before delivering part of the corresponding downstream data to the ONU, and the rest part of downstream data is carried to the ONU by the other bands of the band group in the same time. According to the gate message, the ONU knows its transmission time and sleeping time. In the upstream direction, each band group also selects a band to deliver report messages. This band sends a part of upstream data as well. Once the ONU receives the gate message, it starts upstream transmission through the assigned band group, and transmitting would be stopped at the time that the allocated transmission time elapses. At the end of transmission, the ONU predicts its transmission time requirement for the next transmission window, and uses the report-delivering band to send a report message containing its transmission time requirement before falling to sleep. The sleeping ONU would wake up when the indicated sleeping time elapses. At the OLT end, the OLT collects the report messages from the corresponding ONUs for each band group and calculates the total transmission time needed by a band group in next cycle. Then for the ONUs occupying a same band group, the OLT divides the corresponding total transmission time and allocates time

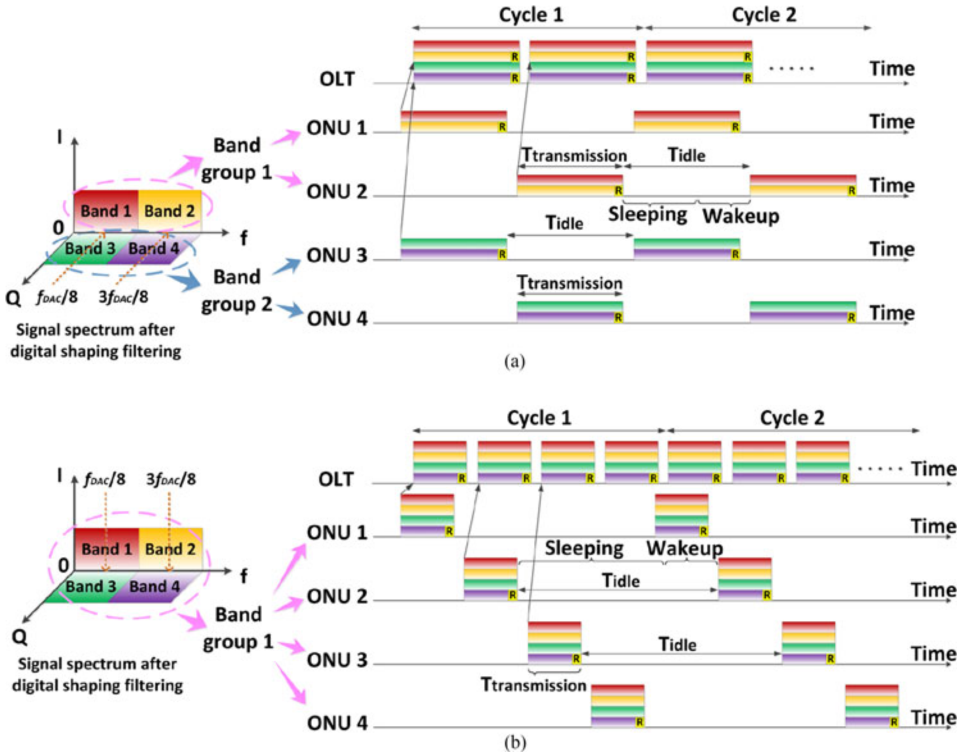

Fig. 2. Upstream traffic flow and band employment in time domain. (a) $m = 2$ bands are assigned in a band group. (b) $m = 4$ bands are assigned in a band group. (R = report.)

slots to each ONU according to its requirement. In the scenario that the available idle time of an ONU is not sufficient to perform sleeping-to-active status transition, the OLT would allocate idle time instead of sleeping time to the ONU to keep the ONU stand by. In this way, the system could perform harmoniously. Moreover, if band reassignment were required, the gate and report messages would help to indicate corresponding ONU to reconfigure its digital filters.

The traffic flow diagram of the TDMBA-PON is shown in Fig. 2. Since upstream and downstream transmissions occur synchronously at each ONU, only upstream traffic flow is depicted for the purpose of instantiation. For simplicity, four ONUs and $k = 4$ are considered here. Therefore, in each direction, four bands can be generated in the I and Q phases at $f_c = f_{DAC}/8$ and $f_c = 3f_{DAC}/8$. As shown in Fig. 2(a), with the setting of $m = 2$, a medium sleeping time is provided to each ONU between two successive transmissions. When m is doubled under the same traffic condition, Fig. 2(b) indicates that the corresponding transmission time is reduced by half, and the available sleeping time of an ONU between two successive transmissions is greatly increased. Mathematically, with respect to the basic DFMA-PON, the energy efficiency of TDMBA-PON at ONU part is

$$\begin{aligned} E_{efficiency} &= \frac{(P_{ONU\_on} + mP_{band})(T_{cycle} - T_{sleeping}) + P_{ONU\_sleeping}T_{sleeping}}{(P_{ONU\_on} + P_{band})T_{cycle}} \\ &= \frac{(P_{ONU\_on} + mP_{band})(T_{transmission} + \alpha) + P_{ONU\_sleeping}(T_{cycle} - T_{transmission} - \alpha)}{(P_{ONU\_on} + P_{band})T_{cycle}} \\ &= \frac{(P_{ONU\_on} + mP_{band})(kData/(f_{DAC/ADC}m) + \alpha)}{(P_{ONU\_on} + P_{band})T_{cycle}} \\ &\quad + \frac{P_{ONU\_sleeping}(T_{cycle} - kData/(f_{DAC/ADC}m) - \alpha)}{(P_{ONU\_on} + P_{band})T_{cycle}}. \end{aligned} \tag{6}$$

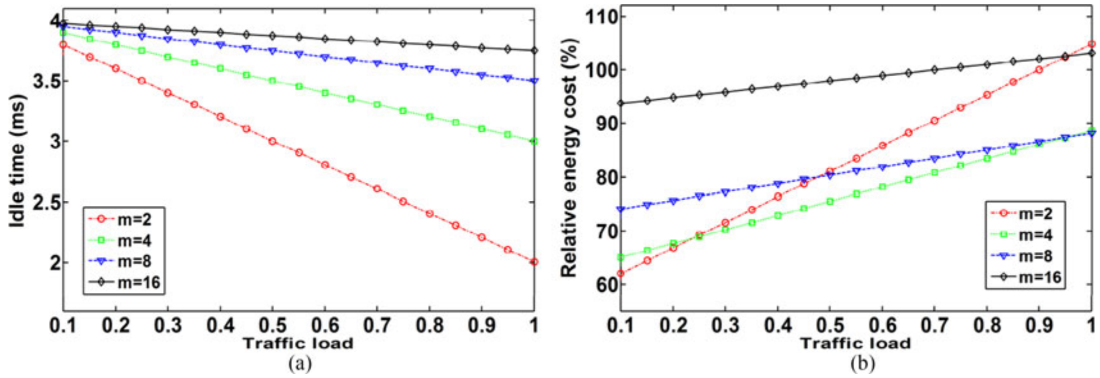

Fig. 3. (a) Average idle time of an ONU in one polling cycle versus traffic load. (b) Relative energy cost at ONU side versus traffic load.

where P_{ONU_on} and $P_{ONU\_sleeping}$ refer to the ONU power costs in active status and sleeping status, respectively, and P_{band} refers to the additional power cost of each band pair used for transmissions in two directions, and *Data* stands for the amount of data that is needed to be delivered in one upstream transmission. It can be concluded that employing a relatively larger m can enhance the energy efficiency by increasing the sleeping time. Nevertheless, according to the property of inverse proportional function, if m is very large, further increasing m could only bring in limited energy efficiency promotion, and a further increased penalty on digital processing complexity is brought to every ONU. In the TDMBA-PON, since high performance DSP module is deployed, the sampling rate of DAC/ADC actually determines the active time of an ONU, and the digital processing penalty induced by increasing m does not affect the sleeping time greatly. Therefore, in this paper, only the power cost penalty of increasing m is in our scope, and the digital processing delay variation caused by increasing m is beyond the scope. Moreover, since the optical power budget of the PON is not affected for the reason that digital filtering and band grouping are performed in the digital domain, achieving the access reach of a conventional access network (25 km) would not be an issue for our proposal according to [13], and the access reach issue and the signal-to-noise performance are not discussed in this paper.

3. Simulation Setup and Results Discussing

In this section, the performance of a TDMBA-PON composed of 16 ONUs ($n = 16$) is evaluated to demonstrate the feasibility of the proposed scheme. The factor k is set to be 16. In the simulations, the sampling rate of DAC/ADC is 15 GS/s, the polling cycle time is set as 4 ms, the wakeup transition time is 2 ms, the propagation delay is 100 μs, the transmission gap time is 1 μs, and the processing delay time for digital filtering is 10 μs [8]. The basic power cost of a DSP and SOA employed ONU is calculated as 7.5 W while 4 W is for DSP module and the other 3.5 W is for optical module, and each pair of bands in charge of transmissions in two directions induces an additional power cost of 0.4 W to the DSP module [17], [18]. Under sleeping status, the power cost of this ONU is reduced to 0.75 W [19]. According to [17], [18], and the sampling rate of DAC/ADC, the line rate of TDMBA-PON is set as 15 Gbit/s for both directions. The normalized traffic load varies in range from 0.1 to 1.

The available idle time of an ONU in one polling cycle is initially investigated. As shown in Fig. 3(a), when the traffic becomes heavier and heavier, the idle time decreases gradually as expected since more and more time is spent for data transmission. It is obvious that a relatively larger m would induce longer idle time, because more bands are allocated to the ONU to increase its transmission bandwidth, and the corresponding transmission time is decreased. This phenomenon is more obvious under the heavy load conditions, for the reason that heavy traffic condition intensifies the transmission time decrement that is caused by providing more bands. However, as a period of time

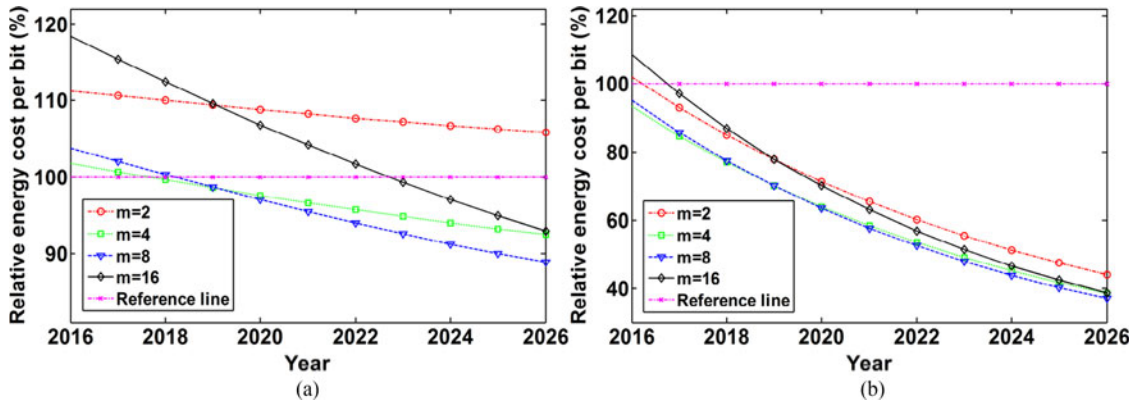

Fig. 4. (a) Relative energy cost to transmit one bit $E_{bit\_TDMBA}/E_{bit\_Conventional} \times 100\%$ versus year. (b) Relative energy cost to transmit one bit with respect to the conventional network deployed in 2015 versus network upgrading year.

is needed for an ONU to perform the wakeup transition, the idle time cannot be fully transformed into sleeping time to save energy. Moreover, processing more bands also means higher power cost at ONU side, and it would finally influence the energy saving performance of the proposed scheme. Therefore, in Fig. 3(b), the ONU energy cost performance of the TDMBA-PON is evaluated in relative to that of the basic DFMA-PON. With the growth of traffic, more time is used to transmit the piled-up data, and the energy cost rises for the decrement of sleeping time. The energy cost curve rises slower in the scenario that a relatively larger m is adopted, since the idle time decreases slower. However, due to the extra power cost induced by applying more bands, part of the energy saving effect of providing longer sleeping time is counteracted. Therefore, the energy saving in the scenario adopting $m = 16$ is small, and the TDMBA-PON would become energy-inefficient under high load conditions in the cases of adopting $m = 2$ and $m = 16$. It is indicated that under low load, adopting a relatively smaller m is more energy-efficient, and a relatively larger m application would be in advance under high load conditions. In general, $m = 4$ can be considered as the optimum band grouping scale, and 12%$\sim$35% of the energy consumed at ONU side could be saved. This result intuitively shows that the proposed scheme could substantially improve the energy efficiency performance of DFMA-PON.

To further evaluate the feasibility of the TDMBA-PON, its average energy cost on transmitting one bit (E_{bit_TDMBA}) is investigated versus technology improvement, and that of a conventional distributed feedback-ONU (DFB-ONU) based 10G PON ($E_{bit\_Conventional}$) is introduced for comparison. Here, on-off keying is adopted for the conventional PON as well to eliminate the influence of modulation format. The basic power cost of the OLT in these two PON systems is set as a value identical to the active power cost of an ONU subordinated to it, while the OLT in the TDMBA-PON suffers an additional power cost of 9.9 W for the requirements of seed laser (+1 W), coherent detector (+2.5 W), and processing all bands (+6.4 W). For the DFB-ONU, its power cost is estimated as 2 W for electronic interface and 3.052 W for optical interface, and its power cost under sleeping status is 0.750 W [6], [10]. In the conventional PON, the Just-In-Time cyclic sleep mechanism proposed in [8] is adopted, and the line rate is 10 Gbits/s for both directions. Other basic network parameters such as number of ONUs, polling cycle time, wakeup transition time, propagation delay, and transmission gap are same as those adopted in the TDMBA-PON. A normalized traffic load of 0.6 is considered for both schemes in the simulation to represent a typical load level of practical access network, and average packet size is set as 791 bytes. According to the power costs reported in [10], [17]–[19], the publication years of these references, and the power cost reduction rules of optical and electrical interfaces reported in [20], Fig. 4(a) shows the relative energy cost $E_{bit\_TDMBA}/E_{bit\_Conventional} \times 100\%$ versus year. In the simulation, four m value cases are evaluated within the year range from 2016 to 2026. A reference line (cross-dot) representing

$E_{bit\_TDMBA}/E_{bit\_Conventional} = 1$ is depicted to compare the energy saving effects clearly. In the area below the reference line, the TDMBA-PON is more energy-efficient, and in the above area, the conventional PON is more energy-efficient. It is shown that before 2018, the TDMBA-PON is relatively energy-inefficient on transmitting one bit due to the penalty of digital processing and coherent detection, and could only possess some inherent advantages such as flexibility in resource allocation and adaptability to software-defined network. However, since the proportion of power consumed by electrical interfaces is larger in TDMBA-PON than in the conventional PON, and the power cost reduction of electrical interfaces is faster than that of optical interfaces [20], the power cost of TDMBA-PON would reduce faster than that of the conventional PON. Therefore, with time goes by, the TDMBA-PON could reverse the sides and starts to stand on the energy-efficient side. By adopting $m = 4$ or $m = 8$, the TDMBA-PON could be more energy-efficient than the conventional PON on transmitting one bit after 2018. This change point is postponed to 2023 if $m = 16$ were adopted. Nevertheless, the TDMBA-PON adopting $m = 2$ would still be relatively energy-inefficient on transmitting one bit in 2026 since the energy saving gained from technology improvement and sleeping time is not able to compensate the energy cost penalty of digital processing and coherent detection. It is notable that the TDMBA-PON adopting $m = 8$ outperforms the TDMBA-PON adopting $m = 4$ after 2019 and consumes the least energy to transmit one bit in the following years. This is because with technology improvement, the power cost on DSP module reduces and less energy is consumed by processing more bands. Thus, the energy saving effect of inducing longer sleeping time would not be severely counteracted. Due to the same reason, the TDMBA-PON adopting $m = 16$ outperforms that adopting $m = 2$ after 2019. However, since adopting $m = 16$ leads the highest power cost penalty on digital processing, the $m = 16$ adopted TDMBA-PON is still energy-inefficient on transmitting one bit in comparison with the $m = 4$ adopted TDMBA-PON in the year range of this simulation. In general, the energy saving effect of TDMBA-PON on transmitting one bit can be enhanced with the past of time, and it can reach to 12% by the year of 2026. It can also be concluded that $m = 8$ is a proper band grouping scale for the proposed scheme for future practical application.

In fact, the power cost of network element would hardly be changed once it is deployed. Therefore, in relative to the conventional 10G PON deployed in 2015, the average energy cost of the TDMBA-PON on transmitting one bit is further investigated, to highlight the energy saving by upgrading the existing network to TDMBA-PON. As shown in Fig. 4(b), energy consumed for transmitting one bit can be reduced by upgrading the network between 2016 and 2017 due to the technology improvement, and more energy could be saved if the network were upgraded in the years afterward. This relative energy saving can be up to nearly 63% by 2026. That is, to network operators, although the maximum energy saving effect of TDMBA-PON on transmitting one bit is about 12% in relative to the conventional network of the same time, more than half of energy consumed for transmitting one bit can be reduced by upgrading the former conventional network to TDMBA-PON. This substantial energy saving effect makes it easy to cover the expenses on network upgrading, and these results would help operators to maximize their profits according to their market circumstances.

In all, the TDMBA-PON considerably improves the energy efficiency performance of DFMA-PON, and it has great potential on energy saving in future years. Although the capital costs of such DSP based ONU and coherent detector based OLT seem relatively high, those networks employing these ONUs and OLT could be easily upgraded to software-defined network and provide great flexibility in resource management and future network construction. These inherent advantages with the energy saving potential make the TDMBA-PON attractive to next generation network. Moreover, with further maturation of digital processing and semiconductor technology, more energy can be saved in the TDMBA-PON, and the capital cost of such ONU would be reduced quickly as well. Hence, capital cost can be easily recovered. Nevertheless, it is worth mentioning that since the access reach issue is not discussed in this paper, the results concluded may not apply to long-reach access scenario. In our future long-reach access network study, this part of work will be investigated.

4. Conclusion

A novel energy-efficient scheme called TDMBA-PON has been proposed and thoroughly investigated for DFMA-PON. In this scheme, multiple sub-bands in digital domain are grouped as a band group, and each band group is instructed to serve multiple ONUs in a time division mode. Under such scenario, the transmission time of ONU is decreased for the increased bandwidth, and some energy is saved by turning the ONU into sleeping mode when it is idle. With more sub-bands assigned in a band group, shorter transmission time can be obtained due to the further enlarged transmission bandwidth, and consequently, longer sleeping time is acquired. Simulation results indicate that the proposed TDMBA-PON has prominent energy saving property, and grouping eight sub-bands as a band group is optimal for future practical application. Compared with the conventional PON system, the TDMBA-PON is more energy-efficient and flexible in future years, and it may be a considerable solution for future energy-efficient optical access network.

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