Energy-efficient WDM-OFDM-PON employing shared OFDM modulation modules in optical line terminal

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Abstract: We propose and experimentally demonstrate a scheme to improve the energy efficiency of wavelength division multiplexing - orthogonal frequency division multiplexing - passive optical networks (WDM-OFDM-PONs). By using an N × M opto-mechanic switch in optical line terminal (OLT), an OFDM modulation module is shared by several channels to deliver data to multiple users with low traffic demands during non-peak hours of the day, thus greatly reducing the number of operating devices and minimizing the energy consumption of the OLT. An experiment utilizing one OFDM modulation module to serve three optical network units (ONUs) in a WDM-OFDM-PON is performed to verify the feasibility of our proposal. Theoretical analysis and numerical calculation show that the proposed scheme can achieve a saving of 23.6% in the energy consumption of the OFDM modulation modules compared to conventional WDM-OFDM-PON.

OCIS codes: (060.2330) Fiber optics communications; (060.4250) Networks.

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1. Introduction

Recent studies show that the amount of energy dissipated by the industry of information and communication technologies (ICT) is growing fast at a rate of ~2 dB/year [1] with the rapid increase of global data traffic [2,3] and massive deployment of new network equipments and devices, leading to unsustainable power requirement [4]. Moreover, the ever-increasing energy consumption by ICT causes a series of issues, such as the emission of greenhouse gases and high operation cost of networks [5,6]. Therefore, great efforts have been dedicated to improving the energy efficiency in all aspects of ICT in the past few years [7–10].

According to Ref [11], network equipments dissipate roughly one third of the total energy consumed by ICT every year. Among this, it is estimated that the contribution of access networks is as high as 70% due to the presence of a huge number of active elements [12]. However, current access networks exhibit poor energy efficiency [13], wasting more than 80% of the total power when the network devices are idle [14]. This is mainly because that the access networks are designed to meet the peak traffic load requirement while the users do not fully utilize the network capacity all the time. Of all kinds of access network schemes, passive optical network (PON) is an energy-saving technique installing passive components at remote node [15].

Wavelength division multiplexing - passive optical network (WDM-PON), as a promising candidate for next-generation PON, gains much attention due to its advantages of high capacity, large coverage range and easy upgradeability. Introducing orthogonal frequency division multiplexing (OFDM) technique to WDM-PON further increases the system capacity and also provides robust dispersion tolerance [16]. WDM-PON with OFDM technique, i.e. WDM-OFDM-PON, has been intensively investigated by many research groups in recent years [17,18]. Nonetheless, from the perspective of energy efficiency, WDM-OFDM-PON utilizes more energy than other PONs (such as EPON/GPON) for two reasons. First, an OFDM modulation module with corresponding light source is needed for each client due to the basic architecture of WDM-PON. In addition, the chips and electrical amplifiers in the OFDM modulation modules for the generation and amplification of electrical OFDM signals consume large amount of power when the data rate increases up to Gb/s, which accounts for the main part of the power dissipated by the optical line terminal (OLT). For EPON/GPON, several approaches have been proposed to improve their energy efficiencies in literatures, such as sleep mode [19], adaptive link rate (ALR) control [20], and OLT-shared design [21]. In contrast, there is little effort devoted to reducing the energy consumption of WDM-OFDM-PON.

In this paper, we propose and experimentally demonstrate a new scheme to improve the energy efficiency in a WDM-OFDM-PON. In our scheme, an N × M opto-mechanic switch in the OLT is employed to dynamically assign OFDM modulation modules consisting of E/O modulators and electrical OFDM signal generators to different users. Several users can share one OFDM modulation module through flexible and adaptive OFDM subcarrier allocation when they have low data bandwidth requirements. Thus, a number of OFDM modulation modules can be turned off, resulting in great reduction of energy consumption.

2. Operation principle

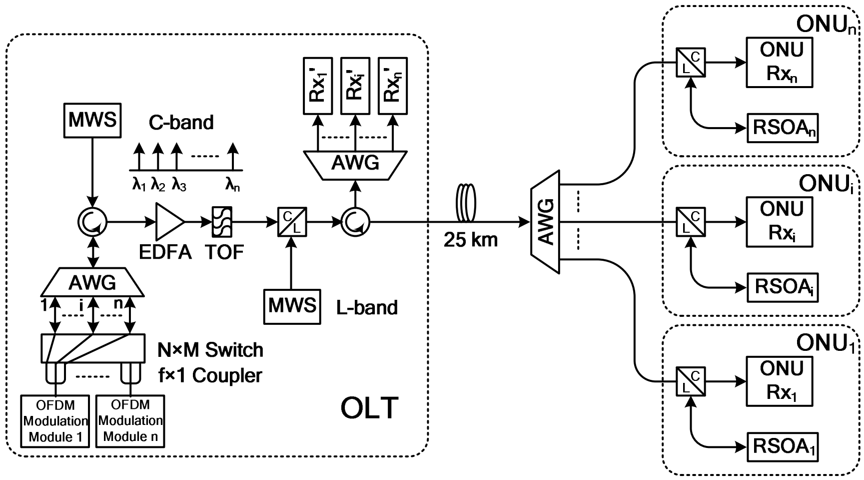

Fig. 1. Schematic diagram of energy-efficient WDM-OFDM-PON using shared OFDM modulation modules.

The schematic diagram of the proposed energy-efficient WDM-OFDM-PON is depicted in Fig. 1. A multiple-wavelength source (MWS) generates N continuous waves (CWs) with identical wavelength spacing in C-band [22]. Through an optical circulator and an arrayed waveguide grating (AWG), the CW lights are wavelength-demultiplexed and output to the N ports of a low-cost N × M opto-mechanic switch as shown in Fig. 1. The opto-mechanic switch has low energy consumption [21] and a typical switching time of several milli-seconds. At the other side of the switch, M ports are connected to the OFDM modulation modules by N f × 1 optical couplers with a relation of M = N × f. Each optical coupler links one OFDM modulation module with f ports of the switch. Here, we define a parameter F as the degree of flexibility (DOF) of the network, representing the maximum number of wavelengths that an OFDM modulation module can modulate. It is easily deduced that the parameter F is determined by the f × 1 optical couplers and F equals f. In the operation mode of energy conservation, k (k ≤ f) CW lights are input into one OFDM modulation module by adjusting the opto-mechanic switch when the total traffic load of k channels is below the maximum transmission capacity of the OFDM modulation module. By this way, k-1 OFDM modulation modules can be powered off, reducing large amount of energy consumption. In the running OFDM modulation module, downlink data in the k channels are combined together to generate an OFDM signal with adaptive subcarrier allocation by digital signal processing (DSP) chip. The electrical OFDM signal is then imposed onto k CW lights and each wavelength carries the combined data of k optical network units (ONUs). The OFDM modulation module reflects the modulated optical signals to the optical coupler and switch by reflective devices such as reflective semiconductor optical amplifier (RSOA). Passing through the AWG and optical circulator, the optical signals are amplified by an erbium doped fiber amplifier (EDFA) to compensate for the loss induced by the optical couplers. A tunable optical filter (TOF) is followed to suppress the amplified spontaneous emission (ASE) noise. Then the optical signals are waveband-multiplexed with a set of wavelengths in L-band as the seeding light sources for uplink modulation. After 25-km standard single mode fiber (SSMF) transmission, another AWG is used to demultiplex the optical signals and route them to individual ONUs. At the ONU side, the downlink optical signals are separated from the

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seeding lights by C/L waveband filters. OFDM receivers (Rxs) implement the O/E conversion and retrieve the data needed by the end users from the optical signals. In addition, RSOAs are utilized to transmit the uplink signals received in the OLT.

It is well known that the traffic load of access networks fluctuates at different hours of the day. In a conventional WDM-OFDM-PON, all OFDM modulation modules have to be running regardless of the current traffic condition. This leads to high energy consumption and low energy efficiency. In our proposal, most under-utilized OFDM modulation modules can be turned off while rerouting their traffic to a few OFDM modulation modules by the N × M opto-mechanic switch reconfiguration during low-load hours. According to real-time traffic loads of different ONUs, an optimum strategy can be achieved to use minimum number of OFDM modulation modules to deliver the data of all ONUs. On the other hand, the additional energy cost incurred by the switch reconfiguration is negligible owing to the low energy consumption of the opto-mechanic switch [21]. Therefore, the energy efficiency of WDM-OFDM-PON is largely improved by the proposed scheme. The numerical analysis will be discussed in detail in section 4.

3. Experimental setup and results

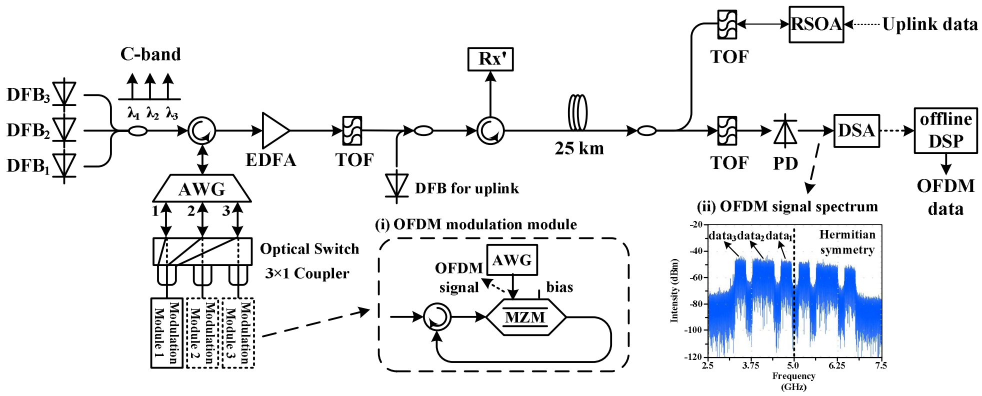

Fig. 2. Experimental setup for energy-efficient WDM-OFDM-PON with shared OFDM modulation modules.

Figure 2 depicts the proof-of-concept experimental setup of the proposed energy-efficient WDM-OFDM-PON. In the OLT, distributed feedback (DFB) lasers provide three CW lights with wavelengths at λ_1 = 1557.2 nm, λ_2 = 1558.0 nm, and λ_3 = 1558.8 nm, respectively. Through an optical coupler, an optical circulator and an AWG, the CW lights are firstly combined together and then wavelength-demultiplexed into three parts. During the non-peak hours of the day, the traffic loads of ONUs are small and in our experiment we assume their downlink data rates are 1.25 Gb/s, 2.5 Gb/s, and 1.25 Gb/s, respectively. In this case, three CW lights are input into one OFDM modulation module with a maximum transmission capability of 10 Gb/s by a 3 × 1 optical coupler. The OFDM modulation module consists of an optical circulator, a Mach-Zehnder modulator (MZM) and an arbitrary waveform generator (Tektronix AWG 7122C) as shown in the inset (i) of Fig. 2. The OFDM data is generated offline by Matlab. The total subcarrier number is 1024. Among those 1024 subcarriers, 256 subcarriers are used for $data_1$, $data_2$, and $data_3$ from three ONUs and 768 subcarriers are set to zero as guard band. The format for each data subcarrier is 16-quadrature amplitude modulation (16-QAM). In order to simplify the configuration of the system, input vector to the IFFT is constrained to have Hermitian symmetry to realize intensity modulation - direct detection (IM-DD) optical OFDM [23]. After the implementation of IFFT, a cyclic prefix of 64 samples is added for mitigating the inter-symbol interference (ISI) caused by chromatic dispersion. Then, the OFDM data generated by Matlab are output by the Tektronix AWG 7122C with 10-GSample/s sampling rate and 8-bit resolution which functions as a digital to

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analog converter (DAC). In the OFDM modulation module, three CW lights are simultaneously modulated by the electrical OFDM signal. Passing through the optical circulators, the 3 × 1 optical coupler and the AWG, the optical signals are amplified by an EDFA. A following TOF is used to suppress the ASE noise. Then the optical signals are coupled with another CW light from a tunable laser at 1575 nm. After transmission of 25-km SSMF, the optical signals are split into two parts. One part goes through another TOF and is O/E converted by a 10-GHz photo detector (PD). The inset (ii) of Fig. 2 illustrates the electrical spectrum of the OFDM signal, where six distinct OFDM sub-bands for three data with a total bandwidth of ~3.5 GHz are observed. A Tektronix real-time oscilloscope (DSA 70804) at 25 GSample/s is followed to sample the electrical signal. The sampled data are digitally processed offline to retrieve the OFDM data. By tuning the central wavelength of TOF, three downlink data are easily obtained for different ONUs. For the uplink transmission, a RSOA is utilized to amplify and transmit the upstream data.

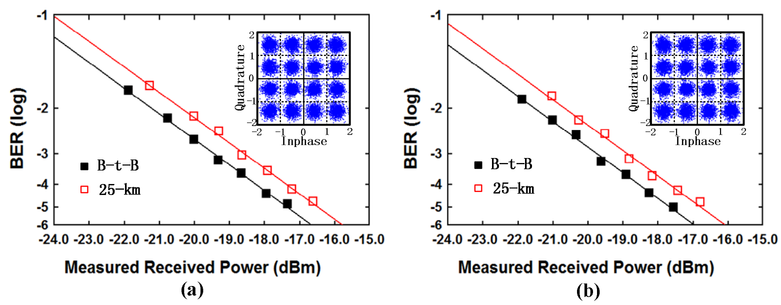

Fig. 3. BER curves of $data_1$ for (a) energy-efficient WDM-OFDM-PON; (b) conventional WDM-OFDM-PON.

By removing the opto-mechanic switch and the optical couplers in the OLT, conventional WDM-OFDM-PON with three ONUs is also experimentally demonstrated, where three data flows and CW lights are injected into three different OFDM modulation modules. Since the three ONUs have almost the same transmission performances, we only consider the downlink data of ONU_1. Figure 3(a) and 3(b) show the BER curves of $data_1$ in the energy-efficient and conventional WDM-OFDM-PONs, respectively. The receiver sensitivity is about −17.2 dBm at a BER level of 10^{-5} in our proposal, which is a little worse than that of conventional WDM-OFDM-PON by ~0.2 dB due to the introduction of the optical switch and coupler. It indicates that our scheme can provide energy saving while maintaining the performance of the access systems. The 25-km transmission of optical fiber brings about 0.8-dB power penalty for both schemes. The insets in Fig. 3(a) and 3(b) show the corresponding constellations of 16-QAM modulated OFDM signals.

4. Numerical analysis for energy efficiency

In order to quantitatively analyze the improvement of the energy efficiency in the proposed scheme, we consider a WDM-OFDM-PON with 32 channels to support 32 users. For the conventional WDM-OFDM-PON, all OFDM modulation modules are required to be active all the time. In contrast, the number of running OFDM modulation modules depends on the traffic demands of ONUs in our proposal. Here, we first develop an appropriate traffic model for the access system. The total transport capacity of the network is C_m and the current traffic in a certain time is C_c. We define a parameter R as offered load ($R = C_c/C_m$). Each ONU has a maximum transport capacity of $c_m = C_m/32$ and a current transmission speed of c_c. The normalized traffic ($r = c_c/c_m$) of ONUs is assumed to be independent and obey normal distribution N(R, σ), where R is the offered load and σ is the variance of the traffic of customers. When $r \le 0$, we suppose the ONU has no data to receive; when $0 < r \le 1$, the ONU has a certain load and can share an OFDM modulation module with other ONUs; when $r \ge 1$, congestion occurs in the ONU and one OFDM modulation module has to be used to transmit data for it. An OFDM modulation module has a maximum transmission capability of $C_m/32$ and can serve as many as F ONUs. F is defined as the DOF of the network as aforementioned in section 2. Figure 4(a) depicts the calculated mathematical expectations of the number of running OFDM modulation modules with the variation of the offered load while F equals 2, 4, 8, 16, and 32. The parameter σ is assumed to be 0.1 to moderate the congestion probability of ONU as R is high. From the figure, it is clearly observed that the energy-efficient WDM-OFDM-PON can significantly reduce the number of operating OFDM modulation modules, allowing for large energy savings. Also, the energy efficiency improves with the decrease of the offered load and the increase of the DOF of the network. However, the improvement is quite small while F ≥ 8. Therefore, the optimum value of the DOF of the energy-efficient WDM-OFDM-PON is set to be 4 in consideration of the system complexity and energy efficiency, which is irrelevant to the number of ONUs. Figure 4(b) shows the number of running OFDM modulation modules with the variation of the offered load while σ has different values. The energy efficiencies of the network are almost the same when σ = 0.05 and 0.1. But the network with σ = 0.5 saves more energy. This is mainly because that the variance of the traffic load of customers becomes larger and the congestion probability increases. It is worth noting that the improvement of the energy efficiency is also determined in part by the behavior patterns of the customers in addition to the DOF and the offered load of the proposed scheme.

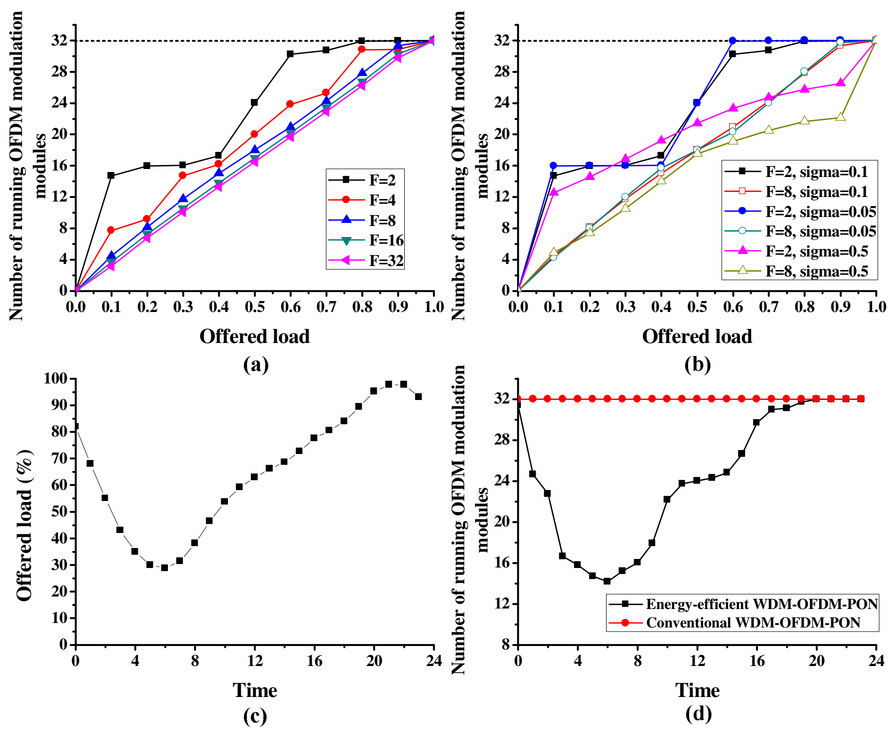

Fig. 4. The calculated mathematical expectations of the number of running OFDM modulation modules with (a) different degrees of flexibility, (b) different variances; (c) The offered load over the course of an average day in North America [24]; (d) Required OFDM modulation modules for energy-efficient (F = 4, σ = 0.1) and conventional WDM-OFDM-PONs versus time in an average day.

Figure 4(c) depicts the network traffic profile in the course of an average day in the fixed access networks of North America [24]. From it, an evident phenomenon is observed that the traffic demands of the users fluctuate during different hours of the day. The lowest traffic of

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the network is only about 29%, occurring at 6 am in the early morning. This implies that the energy-efficient WDM-OFDM-PON can make great improvement on the energy efficiency of the access networks. Figure 4(d) shows the number of OFDM modulation modules required to be up in energy-efficient and conventional WDM-OFDM-PONs, respectively. Here, the DOF of the energy-efficient WDM-OFDM-PON is set to be 4 as aforementioned. The conventional network requires the 32 OFDM modulation modules be running all the time, which is quite energy-inefficient and consumes lots of power. Exploiting the proposed scheme, quite a few OFDM modulation modules can be turned off as shown in Fig. 4(d). The numerical calculation shows that about 23.6% energy saving in the OFDM modulation modules can be achieved by using our scheme compared to the conventional WDM-OFDM-PON.

5. Conclusion

We have proposed an energy-efficient WDM-OFDM-PON using shared OFDM modulation modules to achieve energy saving. A proof-of-concept experiment employing one OFDM modulation module to serve three ONUs is performed and negligible power penalty is introduced compared to conventional WDM-OFDM-PON, validating the feasibility of the proposed scheme. Numerical analysis shows that up to 23.6% of energy consumed by OFDM modulation modules in the OLT can be saved by using our proposal.

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