Energy-efficient optical line terminal for WDM-OFDM-PON based on two-dimensional subcarrier and layer allocation

Xiaofeng Hu,[1] Pan Cao,[1] Zhiming Zhuang,[1] Liang Zhang,[1] Qi Yang,[2] and Yikai Su[1,*]

Abstract: We propose and experimentally demonstrate a scheme to reduce the energy consumption of optical line terminal (OLT) in wavelength division multiplexing - orthogonal frequency division multiplexing - passive optical networks (WDM-OFDM-PONs). In our scheme, a wireless communication technique, termed layered modulation, is introduced to maximize the transmission capacity of OFDM modulation module in the OLT by multiplexing data from different ONU groups with signal-to-noise ratio (SNR) margins onto the same subcarriers. With adaptive and dynamic subcarrier and layer allocation, several ONU groups with low traffic demands can share one OFDM modulation module to deliver their data during non-peak hours of a day, thus greatly reducing the number of running devices and minimizing the energy consumption of the OLT. Numerical calculation shows that an energy efficiency improvement of 28.3% in the OLT can be achieved by using proposed scheme compared to the conventional WDM-OFDM-PON.

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

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1. Introduction

With rapid increase of global data traffic and massive deployment of new network devices and equipments, the energy consumption of network is growing fast and becoming a key environmental, social, and economic issue, receiving great attention in the past few years [1–3]. It was reported that access networks consume about 70% of overall network energy consumption owing to the large quantity of access nodes [4]. However, current access networks exhibit poor energy efficiency. A large portion of energy is wasted by idle devices [5], as the access networks are engineered to satisfy the peak traffic-load requirement. In literatures, many methods have been proposed to reduce the energy consumption of time division multiplexing-passive optical network (TDM-PON) and wavelength division multiplexing (WDM) PON, such as sleep mode [6], adaptive line rate control [7], and pilot-tone-based monitoring technique [8].

Optical orthogonal frequency division multiplexing (OFDM) technique has recently been a promising technique in access networks due to its high spectral efficiency and robust dispersion tolerance [9]. WDM-OFDM-PON, combining the advantages of WDM and OFDM techniques, can provide higher data rate and more flexible bandwidth allocation for end users, which has been intensively investigated by many research groups [10–12]. Nonetheless, OFDM modulation modules, consisting of high-speed digital signal processing (DSP) chips, digital-to-analog converters (DAC), and E/O modulators, are needed for the generation of optical OFDM signals in WDM-OFDM-PON. These components consume much more energy than the counterparts in conventional TDM-PON and WDM-PON, especially when the data rate increases up to 10 Gb/s. Moreover, each OFDM modulation module is fixed for one optical network unit (ONU) group in conventional WDM-OFDM-PON, which causes a rough granularity and wastes a large amount of bandwidth resource since the users do not fully utilize the network capacity all the time. Therefore, it is of great significance to design an energy-efficient WDM-OFDM-PON system. To date, however, there are few reports concentrating on improving the energy efficiency of WDM-OFDM-PON.

In our previous work [13], a method of sharing OFDM modulation modules based on subcarrier allocation is used to save the energy consumption of WDM-OFDM-PON. Subcarrier allocation is a simple technique that every ONU is allocated with a certain number of subcarriers to transmit data in accordance with its real-time traffic demand. Due to the differences of the received signal-to-noise ratios (SNRs) at the ONU side, the modulation formats in the subcarriers assigned to different ONUs should be properly designed to guarantee the system performance. Nonetheless, this approach, often referred to bit loading [14], does not fully utilize the limited bandwidth offered by OFDM modulation modules when some ONUs still have spare SNR margins which are however not enough to upgrade the modulation formats employed by the ONUs to higher order constellations, e.g. from quadrature phase shift keying (QPSK) to 16 quadrature amplitude modulation (16QAM). In this paper, we introduce a new technique, termed layered modulation [15,16], to maximize the use of the remaining SNR margins in WDM-OFDM-PON system by multiplexing data from the ONUs with different SNRs onto the same subcarriers, thereby greatly increasing the transmission capacity of every single OFDM modulation module in the optical line terminal (OLT). By combining the subcarrier allocation with the layer allocation, our scheme enables the delivery of data for all ONUs with the minimum number of OFDM modulation modules according to current network traffic loads, thus powering off other OFDM modulation modules and reducing the energy consumption of the OLT of WDM-OFDM-PON.

2. Operation principle

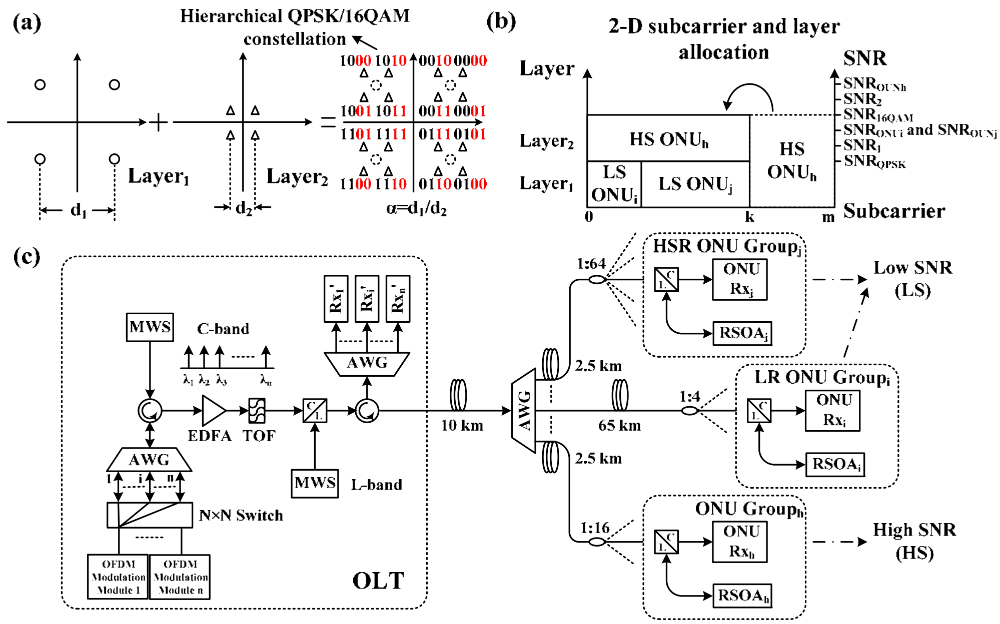

Fig. 1. (a) QPSK/16QAM layered modulation. (b) Two-dimensional subcarrier and layer allocation (LS: low-SNR; HS: high-SNR). (c) Schematic diagram of the proposed energy-efficient WDM-OFDM-PON (LR: long-reach; HSR: high-split-ratio).

Layered modulation, also termed hierarchical modulation, is one of the wireless communication technologies for multiplexing and modulating multiple data streams into one single symbol stream. Although layered modulation can be implemented in many constellations, we limit our discussions to hierarchical QPSK/16QAM format in this paper for simplicity. Figure 1(a) describes the principle of QPSK/16QAM layered modulation. Two separate and independent data streams, $data_1$ and $data_2$, are mapped onto $Layer_1$ and $Layer_2$ with QPSK constellations, respectively. The two QPSK symbols are then superimposed together to constitute a 16QAM symbol. The mapping of the information bits is indicated in the hierarchical QPSK/16QAM constellation in Fig. 1(a), where the first two bits represent the data in the $Layer_1$ and the two remaining bits represent the data in the $Layer_2$ [15]. The minimum distances between adjacent points in two QPSK constellations are denoted by d_1 and d_2, respectively. Since d_1 is larger than d_2, $data_1$ shows better bit error rate (BER) performance than $data_2$ at the same receiving condition when hierarchical QPSK/16QAM signal is transmitted [16]. Here, we define SNR_1, SNR_2, SNR_{QPSK}, and SNR_{16QAM} as the required minimum SNRs to achieve error-free transmission for $data_1$ and $data_2$ in hierarchical QPSK/16QAM signal, QPSK signal and 16QAM signal, respectively. In addition, we also define a hierarchical parameter α as the ratio of d_1 to d_2 ($\alpha = d_1/d_2$). With the increase of α, SNR_1 is decreased at the cost of the increase of SNR_2. Based on the analysis in Ref [15,16], an inequality, $_2 \geq$ $_{16}$ $\geq$ $_1 \geq$, can be obtained.

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The basic principle of our proposed two-dimensional (2-D) subcarrier and layer allocation is depicted in Fig. 1(b). Owing to diverse transmission and reception conditions, the received SNRs of ONU groups are different. For instance, the SNRs of long-reach ONU Group_i and high-split-ratio ONU Group_j (SNR_{ONUi} and SNR_{ONUj}) in Fig. 1(c) are relatively low, while the SNR of general ONU Group_h (SNR_{ONUh}) is high. Normally, the modulation format in the subcarriers allocated to the ONU depends on the SNR of that ONU, which is referred to bit loading technique [14]. We assume that the SNRs of three ONU groups in Fig. 1(c) meet the inequality $\geq {}_{16} \geq {}_{,} \geq$. Thus, by employing subcarrier allocation and bit loading technique, subcarriers with QPSK constellation are assigned to ONU Group_i and Group_j to ensure error-free transmission, while subcarriers with 16QAM format are assigned to ONU Group_h. However, if the ONUs still have some remaining SNR margins satisfying the inequality:

$$\geq {}_{2} \geq {}_{16} \geq {}_{,} \geq {}_{1} \geq \quad (1)$$

a hierarchical QPSK/16QAM modulation format can be employed in the QPSK-modulated subcarriers. As shown in Fig. 1(b), data of ONU Group_h originally carried by the last subcarriers is moved onto Layer_2 of the hierarchical QPSK/16QAM constellation in the first subcarriers. Meantime, data of ONU Group_i and Group_j are mapped onto Layer_1 of the first subcarriers. This allocation scheme is referred to 2D subcarrier and layer allocation in our paper. By controlling the hierarchical parameter α, one can adaptively adjust SNR_1 and SNR_2 to meet the above inequality, achieving error-free operation. Thus, subcarriers originally assigned to ONU Group_h can be re-allocated to other ONU groups, greatly increasing the transmission capacity of OFDM modulation module. It is worth noting that the hierarchical modulation formats and hierarchical parameter can be properly adjusted according to the practical access network conditions.

Figure 1(c) shows the schematic diagram of the proposed energy-efficient WDM-OFDM-PON. In the OLT, continuous waves (CWs) in C-band are generated by a multi-wavelength source (MWS). Through an optical circulator, an arrayed waveguide grating (AWG), and an N × N optical switch, the CW lights are input into the OFDM modulation modules. During non-peak hours of the day, CW lights can be routed into one OFDM modulation module with the use of the optical switch when the total traffic load of channels is below the maximum transmission capacity of the OFDM modulation module. Meanwhile, other OFDM modulation modules can be shut down. Here, we define a parameter F as the degree of flexibility (DOF) of the network, representing the maximum number of CW lights that an OFDM modulation module can modulate. In the operating OFDM modules, CW lights are modulated by OFDM data to generate the downstream optical OFDM signal. The generated optical signal then passes through the optical switch and AWG, and is subsequently launched into an erbium doped fiber amplifier (EDFA). After amplification and filtering, the optical OFDM signal is waveband-multiplexed with another CW lights in L-band which are used as seeding light sources for the upstream link. Through an optical circulator and a 10-km standard single-mode fiber (SSMF), the optical signal is demultiplexed by another AWG and delivered to individual ONU groups. At the ONU side, the downlink OFDM signals are separated from the seeding lights by C/L waveband filters. Then, the data needed by the end users are retrieved by OFDM receivers (Rxs). For the upstream transmission, reflective semiconductor optical amplifiers (RSOAs) are utilized to modulate and amplify the upstream signal.

It is well known that the traffic load of access networks fluctuates during the course of a day, mainly determined by the behavior patterns of the customers. For conventional WDM-OFDM-PON, all the OFDM modulation modules have to be running all the time. However, in our proposal, by using dynamic reconfiguration of optical switch and 2-D subcarrier and layer allocation in the OLT, all ONU groups can share the least number of OFDM modulation modules to deliver data according to network traffic demands, thus powering off other OFDM

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modulation modules and therefore reducing the energy consumption of the OLT of WDM-OFDM-PON.

3. Experimental setup and results

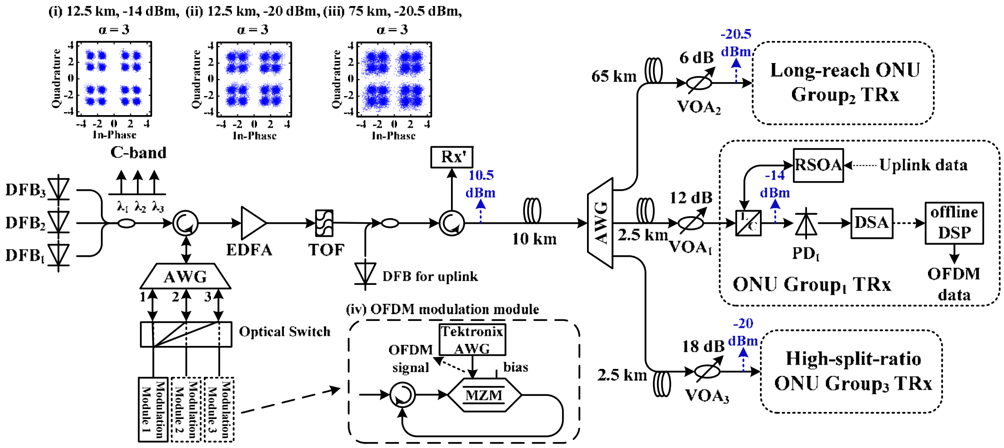

Fig. 2. Experimental setup for energy-efficient WDM-OFDM-PON based on 2-D subcarrier and layer allocation.

Figure 2 shows a proof-of-concept experimental setup of the proposed energy-efficient WDM-OFDM-PON, utilizing one OFDM modulation module in the OLT to serve three ONU groups with different transmission distances and split ratios. During non-peak hours of a day, the traffic demands of ONU groups are usually low and we assume that the downstream data rates are 2.5 Gb/s, 1.25 Gb/s, and 1.25 Gb/s for three ONU groups, respectively. Therefore, only one OFDM modulation module with a transmission capacity of 10 Gb/s needs to be turned on to deliver data to all the ONUs. In Fig. 2, three CW lights with wavelengths at 1557.2 nm, 1558 nm, and 1558.8 nm from distributed feedback (DFB) lasers are coupled together by an optical coupler in the OLT. Through an optical circulator, the CW lights are wavelength-demultiplexed by an AWG and then input into an optical switch. In our experiment, three CW lights are all routed into the first OFDM modulation module by the optical switch according to the above assumption. The module is composed of a single-drive Mach-Zehnder modulator (MZM), an optical circulator, and an arbitrary waveform generator (Tektronix AWG 7122C), and driven by an electrical OFDM signal. The OFDM signal is generated offline by Matlab. The total subcarrier number is 256, in which 128 subcarriers are used for payload from three ONU groups and others are set to zero as guard band. Each data subcarrier is modulated with 16QAM format. After mapping, a 256-point IFFT with Hermitian symmetry [17] is conducted to provide real numerical output data and a cyclic prefix of 20 samples is added to alleviate the inter-symbol interference incurred by chromatic dispersion. Then, the OFDM data is output by Tektronix AWG with 5 GSample/s sampling rate and 8-bit resolution. After the E/O conversion in the OFDM modulation module, the generated optical OFDM signal is fed back into the optical switch and AWG and amplified by an EDFA. Through a tunable optical filter (TOF), the downstream OFDM signal is coupled with another CW light at 1575 nm and then launched into a 10-km SSMF. After transmission, the optical signal is demultiplexed by another AWG and routed to individual ONU groups with different distributed fibers. At the ONU side, variable optical attenuators (VOAs) are used to emulate the optical splitters. Then, the optical OFDM signal in each ONU is detected by a 10-GHz photo detector (PD) and sampled by a real-time oscilloscope (DSA 70804) with a sampling rate of 25 GSample/s. The obtained sampling data is computed and decoded offline and each ONU selects the required data from the subcarriers and layers assigned to it.

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For the uplink transmission, an RSOA is employed to amplify and transmit the upstream signal.

In Fig. 2, we also mark the optical signal powers at the output port of the OLT and input ports of three ONUs. The output optical power of downstream OFDM signal in each wavelength is about 5 dBm in the OLT. On the other hand, it is easy to understand that the receiver sensitivity in ONU $Group_2$ is worse than that in ONU $Group_{1,3}$ due to the longer fiber transmission. The minimum received power for the conventional downstream 16QAM-OFDM signal to achieve a BER of 2×10^{-3} is approximately −18.3 dBm for ONU $Group_2$ as shown in Fig. 3(b). With the use of forward error correction (FEC) module, error-free transmission can be achieved. Thus, the power budget of our system is ~23.3 dB considering the worst receiver sensitivity of −18.3 dBm for conventional 16QAM-OFDM signal.

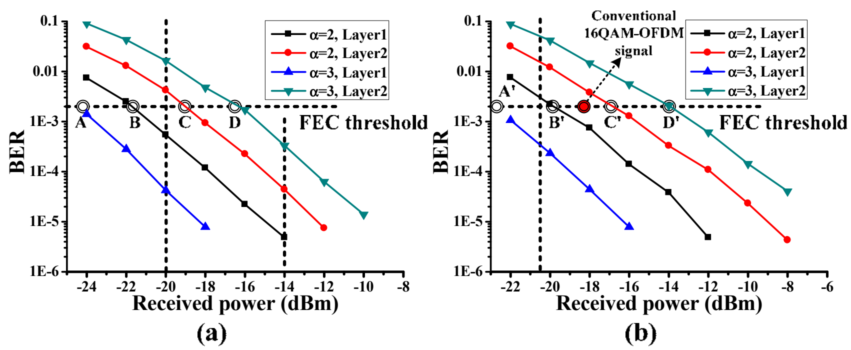

Fig. 3. BER curves for hierarchical QPSK/16QAM signals with α = 2 and 3 after (a) 12.5-km transmission, (b) 75-km transmission (FEC threshold: 2×10^{-3}).

Figure 3 shows the BER curves for downstream hierarchical QPSK/16QAM signals after transmission of 12.5-km and 75-km SSMF, which are obtained by offline Matlab processing. In a PON system, received powers can be used to evaluate the network performance instead of SNRs. The cross points A-D and A'-D' in Fig. 3 denote the required minimum received powers (P_A-P_D, $P_{A'}$-$P_{D'}$) to achieve a BER of 2×10^{-3} for data on two layers in hierarchical QPSK/16QAM signal with α = 2 or 3. Here, we assume that error-free transmission can be realized at these points taking into account the use of FEC module. It is clearly observed that P_C and P_D are higher than P_A and P_B, demonstrating that the BER performance of data on $Layer_1$ is better than that on $Layer_2$ when QPSK/16QAM layered modulation is implemented. In our experiment, the received powers at the ONUs of ONU $Group_1$ are −14 dBm and those of long-reach ONU $Group_2$ and high-split-ratio ONU $Group_3$ are −20.5 dBm and −20 dBm, respectively. As shown in Fig. 3(a), P_A and P_B are lower than −20 dBm, while P_C and P_D are lower than −14 dBm but higher than −20 dBm. It indicates that the data from high-split-ratio ONU $Group_3$ should be mapped onto $Layer_1$ of QPSK/16QAM symbol, while the data from ONU $Group_1$ can be modulated on both layers. For long-reach ONU $Group_2$, the data should be loaded onto $Layer_1$ of hierarchical QPSK/16QAM symbol with α = 3 since only $P_{A'}$ is lower than −20.5 dBm as shown in Fig. 3(b). Thus, only QPSK format can be employed in the subcarriers allocated to ONU $Group_2$ and $Group_3$ if one uses bit loading technique. In order to maximize the transmission capacity of OFDM modulation module, the hierarchical QPSK/16QAM modulation format with α = 3 is used in our experiment with $Layer_1$ delivering the data from ONU $Group_2$ and $Group_3$, and $Layer_2$ transmitting data for ONU $Group_1$, respectively. Based on the above analysis, error-free transmissions are achieved for all data from three ONU groups.

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4. Numerical analysis for energy efficiency

In order to quantitatively analyze the energy efficiency of the proposed scheme, we consider an OLT with 32 OFDM modulation modules supporting 16 general ONU groups, 8 long-reach ONU groups, and 8 high-split-ratio ONU groups in a WDM-OFDM-PON. Based on above experimental results, ONUs in long-reach ONU groups and high-split-ratio ONU groups can only use the QPSK format for error-free transmission. However, through the utilization of layered modulation, the hierarchical QPSK/16QAM format can be applied in those ONUs with $Layer_2$ transmitting data for other ONUs with high SNR, thereby increasing the capacity and energy efficiency of OFDM modulation modules. Here, we define offered load as the ratio of current traffic volume over the maximum system-supported capability. By using the numerical analysis method and premises in Ref [13], we obtain the calculated mathematical expectations of the number of running OFDM modulation modules with the variance of offered load when the DOF of network equals 2, 4, 8, 16, and 32 in Fig. 4(a). It is observed that a large portion of OFDM modulation modules in the OLT can be powered off according to real-time traffic loads. Compared to the data presented in our previous work [13], the number of operating OFDM modulation modules is further reduced mainly due to the introduction of layer allocation. In addition, the energy consumption of OLT is also reduced with the increase of the DOF. Considering the system complexity and cost, the DOF value is chosen as 4 in our analysis. Figure 4(b) provides a traffic profile over time in a 24-hour period in the fixed access networks of North America [18]. From the figure, one can see an obvious phenomenon that the traffic demands from customers fluctuate during the course of a day. For conventional WDM-OFDM-PON, 32 OFDM modulation modules have to be running all the time regardless of the fluctuation of real-time traffic loads. In contrast, quite a few OFDM modulation modules can be turned off by using our proposal as shown in Fig. 4(c), resulting in 43.7% power saving in the OFDM modulation modules.

Based on the data provided in Ref [19,20], we estimate that the power consumptions of OFDM modulation module, DFB laser, optical switch, EDFA, and upstream receiver are 8 W, 1 W, 5 W, 6 W, and 2 W, respectively. Thus, the total power consumption of the OLT is 395 W in the conventional 32-wavelength WDM-OFDM-PON. By using 2D subcarrier and layer allocation, a power saving of 43.7% in the OFDM modulation modules can be achieved, corresponding to 111.9-W power reduction. Therefore, our proposed scheme improves the energy efficiency of the OLT by ~28.3%.

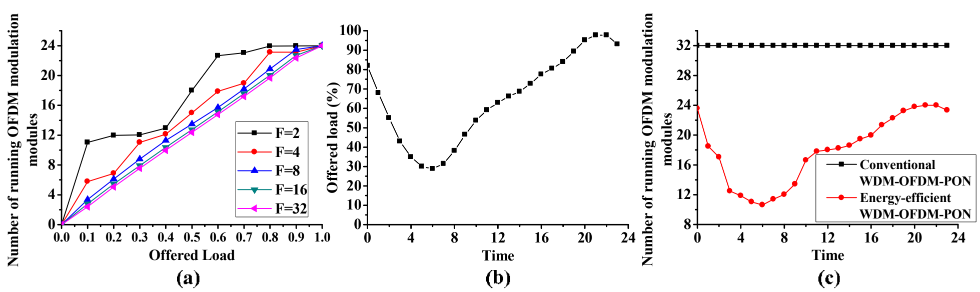

Fig. 4. (a) Calculated mathematical expectations of the number of running OFDM modulation modules with different degrees of flexibility. (b) Offered load over the course of an average day in North America [18]. (c) Required OFDM modulation modules for energy-efficient (F = 4) and conventional WDM-OFDM-PONs versus time in an average day.

5. Conclusion

We have proposed and demonstrated a scheme to realize energy-efficient OLT for WDM-OFDM-PON by sharing OFDM modulation modules with 2-D subcarrier and layer allocation. A proof-of-concept experiment utilizing one OFDM modulation module to serve three ONU groups is performed, verifying the feasibility of our proposal. Numerical analysis results show that up to 28.3% energy saving in the OLT can be achieved by using the proposed scheme.

Acknowledgments

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