Energy-efficient optical network units for OFDM PON based on time-domain interleaved OFDM technique

Xiaofeng Hu, Pan Cao, Liang Zhang, Lipeng Jiang, and Yikai Su*

State Key Lab of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
*yikaisu@sjtu.edu.cn

Abstract: We propose and experimentally demonstrate a new scheme to reduce the energy consumption of optical network units (ONUs) in orthogonal frequency division multiplexing passive optical networks (OFDM PONs) by using time-domain interleaved OFDM (TI-OFDM) technique. In a conventional OFDM PON, each ONU has to process the complete downstream broadcast OFDM signal with a high sampling rate and a large FFT size to retrieve its required data, even if it employs a portion of OFDM subcarriers. However, in our scheme, the ONU only needs to sample and process one data group from the downlink TI-OFDM signal, effectively reducing the sampling rate and the FFT size of the ONU. Thus, the energy efficiency of ONUs in OFDM PONs can be greatly improved. A proof-of-concept experiment is conducted to verify the feasibility of the proposed scheme. Compared to the conventional OFDM PON, our proposal can save 17.1% and 26.7% energy consumption of ONUs by halving and quartering the sampling rate and the FFT size of ONUs with the use of the TI-OFDM technology.

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

References and links

1. N. Cvijetic, "OFDM for next-generation optical access networks," J. Lightwave Technol. **30**(4), 384–398 (2012).
2. D. Qian, N. Cvijetic, J. Hu, and T. Wang, "A novel OFDMA-PON architecture with source-free ONUs for next-generation optical access networks," IEEE Photon. Technol. Lett. **21**(17), 1265–1267 (2009).
3. E. Wong, "Next-generation broadband access networks and technologies," J. Lightwave Technol. **30**(4), 597–608 (2012).
4. B. Liu, X. Xin, L. Zhang, J. Yu, Q. Zhang, and C. Yu, "A WDM-OFDM-PON architecture with centralized lightwave and PolSK-modulated multicast overlay," Opt. Express **18**(3), 2137–2143 (2010).
5. D. Qian, N. Cvijetic, J. Hu, and T. Wang, "108 Gb/s OFDMA-PON with polarization multiplexing and direct detection," J. Lightwave Technol. **28**(4), 484–493 (2010).
6. M.-F. Huang, J. Yu, D. Qian, N. Cvijetic, and G.-K. Chang, "Lightwave centralized WDM-OFDM-PON network employing cost-effective directly modulated laser," in Proc. OFC 2009, San Diego, California, America, paper OMV5.
7. B. Skubic, E. Betou, T. Ayhan, and S. Dahlfort, "Energy-efficient next-generation optical access networks," IEEE Commun. Mag. **50**(1), 122–127 (2012).
8. H. Kimura, H. Nakamura, S. Kimura, and N. Yoshimoto, "Numerical analysis of dynamic SNR management by controlling DSP calculation precision for energy-efficient OFDM-PON," IEEE Photon. Technol. Lett. **24**(23), 2132–2135 (2012).
9. J. Zhang, J. Hu, D. Qian, and T. Wang, "Energy efficient OFDM transceiver design based on traffic tracking and adaptive bandwidth adjustment," Opt. Express **19**(26), B983–B988 (2011).
10. X. Hu, L. Zhang, P. Cao, K. Wang, and Y. Su, "Energy-efficient WDM-OFDM-PON employing shared OFDM modulation modules in optical line terminal," Opt. Express **20**(7), 8071–8077 (2012).
11. X. Hu, P. Cao, Z. Zhuang, L. Zhang, Q. Yang, and Y. Su, "Energy-efficient optical line terminal for WDM-OFDM-PON based on two-dimensional subcarrier and layer allocation," Opt. Express **20**(23), 25284–25291 (2012).
12. K. Kanonakis and I. Tomkos, "Energy-efficient OFDMA-PON exploiting modular OLT/ONU digital signal processing," in *Proc. OFC 2013*, Anaheim, California, America, paper OTh3A.4.

#205194 - $15.00 USD Received 21 Jan 2014; revised 5 Mar 2014; accepted 5 Mar 2014; published 22 May 2014

13. C. Van Praet, H. Chow, D. Suvakovic, D. Van Veen, A. Dupas, R. Boislaigue, R. Farah, M. F. Lau, J. Galaro, G. Qua, N. P. Anthapadmanabhan, G. Torfs, X. Yin, and P. Vetter, "Demonstration of low-power bit-interleaving TDM PON," Opt. Express **20**(26), B7–B14 (2012).
14. C. Van Praet, G. Torfs, Z. Li, X. Yin, D. Suvakovic, H. Chow, X. Qiu, and P. Vetter, "10 Gbit/s bit interleaving CDR for low-power PON," Electron. Lett. **48**(21), 1361–1363 (2012).
15. B. Schmidt, A. Lowery, and J. Armstrong, "Experimental demonstrations of electronic dispersion compensation for long-haul transmission using direct-detection optical OFDM," J. Lightwave Technol. **26**(1), 196–203 (2008).
16. B. Schmidt, A. Lowery, and J. Armstrong, "Experimental demonstrations of 20 Gbit/s direct-detection optical OFDM and 12 Gbit/s with a colorless transmitter," in *Proc. OFC 2007*, Anaheim, California, America, paper PDP18.
17. B. Sedighi, K. Lee, R. Tucker, H. Chow, and P. Vetter, "Energy efficiency in future 40-Gb/s fiber access networks," in *Proc. OFC 2012*, Los Angeles, America, paper JTh2A.
18. Sandvine, "Global Internet Phenomena Spotlight – North America, Fixed Access, Spring 2011" (Sandvine, 2011). *http://www.sandvine.com/news/global_broadband_trends.asp.*

1. Introduction

Due to its high spectral efficiency, flexible bandwidth allocation, and robust dispersion tolerance, orthogonal frequency division multiplexing passive optical network (OFDM PON) has attracted great interests in recent years as a promising solution to future-proof broadband access [1–6]. However, from the perspective of energy efficiency, OFDM PON consumes much more energy than time division multiplexing (TDM) PON, since it employs a great number of energy-hungry analog-to-digital converters/digital-to-analog converters (ADCs/DACs) and digital signal processing (DSP) chips [7]. In order to reduce the energy consumption of OFDM PONs, several approaches have been reported in literatures, which employ variable precision DSP chip [8] and traffic-adaptive OFDM transceiver [9]. Also, in our previous works, two schemes utilizing shared OFDM transceiver [10] and hierarchical modulation technology [11] were proposed to improve the energy efficiency of optical line terminal (OLT) in OFDM PONs.

In an OFDM PON, there are typically tens of optical network units (ONUs) and one OLT. Therefore, the energy dissipated by ONUs accounts for a large portion of the total energy consumption of the PON system, which is about 80% according to Ref [7,12]. On the other hand, the ONUs exhibit poor energy efficiency because they must process the complete downlink OFDM signal with a high data rate to retrieve their own data even though they only occupy a few number of OFDM subcarriers. In TDM PONs, a technique of bit interleaving was proposed to overcome a similar issue [13,14]. Nonetheless, there still have no efforts to resolve this problem in OFDM PONs, which is more serious due to the employment of ADC/DAC and DSP chips with high energy consumption in the ONUs.

In this paper, we propose a time-domain interleaved OFDM (TI-OFDM) technique to improve the energy efficiency of ONUs for OFDM PONs. In the OLT, the data transmitted to the ONUs are divided into multiple groups, which are separately processed by IFFT with a small number of points to obtain several OFDM signals. The TI-OFDM signal is generated by interleaving the OFDM signals in the time domain and then delivered to the ONUs. Each ONU samples and processes one group of data from the TI-OFDM signal with a low sampling rate and a small FFT size to recover its required data. Since a high-speed ADC is usually composed of multiple paralleled low-speed sub-ADC modules, a part of ADC chip can be powered off when the sampling rate decreases [9]. Moreover, the computation amount of the DSP chip in the ONU is reduced with the decrease of the FFT size [12]. Thus, the energy consumed by the ONUs in the OFDM PON can be effectively saved by using our proposed TI-OFDM technique. A proof-of-concept experiment is performed to achieve 17.1% and 26.7% energy savings of ONUs by dividing the downstream data into two and four groups, respectively, by using the TI-OFDM technique. It is worth noting that a trade-off between the number of data groups and the network performance should be made since the TI-OFDM technique would induce more power penalty for the OFDM system with the increase of the number of data groups.

#205194 - $15.00 USD Received 21 Jan 2014; revised 5 Mar 2014; accepted 5 Mar 2014; published 22 May 2014

2. Operation principle

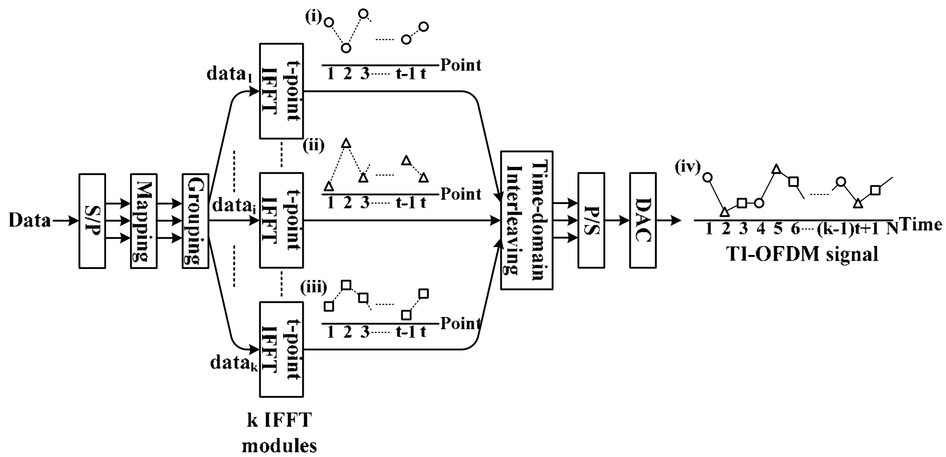

Fig. 1. Basic principle of time-domain interleaved OFDM (TI-OFDM) technique.

The basic principle of the proposed TI-OFDM technique is depicted in Fig. 1. The input binary data is firstly converted to *N* paralleled data strings through a serial-to-parallel converter. With constellation mapping, the data strings are transformed to symbol strings, which are then divided into *k* data groups ($data_1$, $data_2$,…, $data_k$). Each group is processed by *t*-point IFFT to generate an OFDM signal as shown in the insets (i-iii) of Fig. 1. *N*, *k*, and *t* meet the relationship of $N = k \times t$. The TI-OFDM signal is formed by interleaving the *k* OFDM data in the time domain. After parallel-to-serial conversion, the TI-OFDM signal is output by a DAC as described in the inset (iv) of Fig. 1, in which each frame contains *N* data points from *k* different groups. At the receiver, one can simply sample and process the required data group from the TI-OFDM signal to obtain its information data. Compared to the conventional OFDM signal generated by *N*-point IFFT, the TI-OFDM technique greatly reduces the sampling rate and the FFT size of the receiver while maintaining the same frame rate for the DSP chips.

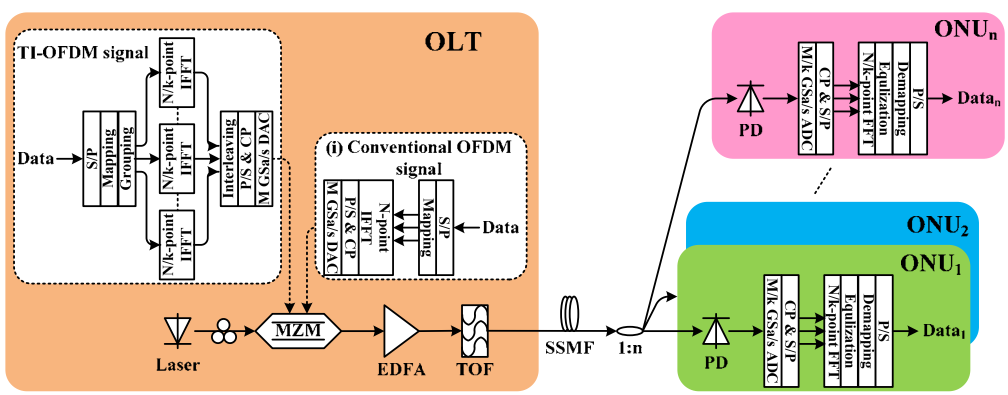

Fig. 2. Schematic diagram of the proposed energy-efficient ONUs in the OFDM PON by using the TI-OFDM technique.

Figure 2 describes the schematic diagram of the energy-efficient OFDM PON based on the TI-OFDM technique. At the OLT, a continue wave (CW) light is injected into a Mach-Zehnder modulator (MZM), which is driven by an electrical OFDM signal. In a conventional OFDM PON, the input data transmitted to all ONUs is processed by an *N*-point IFFT to generate the OFDM signal as shown in the inset (i) of Fig. 2. However, in our scheme, the input data are divided into k data groups and each group contains the data of one or several ONUs. After N/k-point IFFT, the k OFDM data are interleaved to produce a TI-OFDM signal, which is then output by a DAC with a sampling rate of M GSa/s. Through E/O conversion in the MZM, the optical TI-OFDM signal is generated and launched into an erbium doped fiber amplifier (EDFA). A following tunable optical filter (TOF) is used to suppress the amplified spontaneous emission (ASE) noise. After standard single mode fiber (SSMF) transmission, the downstream TI-OFDM signal is split into n parts by an optical splitter. Each part is routed and delivered individually to an ONU by a distribution fiber. At the ONU, the optical TI-OFDM signal is detected by a photo detector (PD). By matching the synchronization message transmitted to the ONU from the OLT [14], the ADC with an appropriate time delay in each ONU samples one group of data from the TI-OFDM signal, which includes the information data required by that ONU. After converting from serial to parallel format and removing cyclic prefix, the sampled data is processed by N/k-point FFT and corrected by an equalizer to retrieve the required data. Generally, each ONU in the conventional OFDM PON has to sample and process the data transmitted to all ONUs with a sampling rate of M GSa/s and a FFT size of N. Nonetheless, by using our proposed TI-OFDM technique, the sampling rate and the FFT size of the ONUs are reduced to M/k GSa/s and N/k points. Since the energy consumed by the ADC and DSP chips accounts for a great part of the total energy consumption of ONUs [7,12], the energy efficiency is improved for the ONUs in OFDM PON by exploiting the proposed TI-OFDM technique.

3. Experimental setup and results

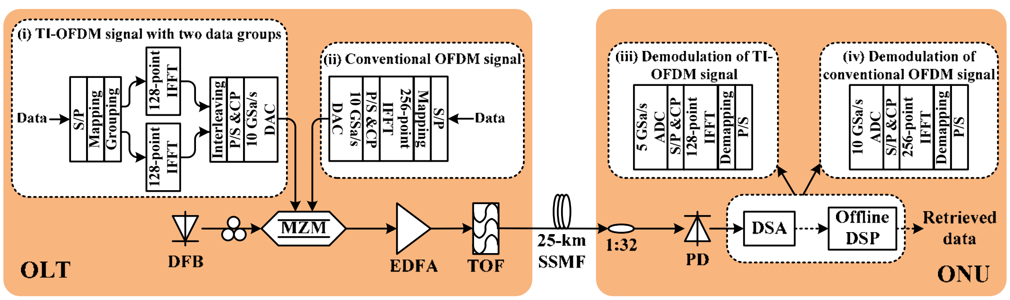

Fig. 3. Experimental setup for energy-efficient ONUs in OFDM PON by using the proposed TI-OFDM technique.

Figure 3 shows the proof-of-concept experimental setup of OFDM PON with energy-efficient ONUs based on the proposed TI-OFDM technology. In the OLT, a CW light at 1558 nm from a distributed feedback (DFB) laser is fed into a 10-GHz single-drive MZM. The MZM is biased just above the null point of the transmission curve and driven by an electrical OFDM signal. We assume that there are 32 ONUs and each ONU has a data rate of 320 Mb/s, thus the total traffic of OFDM PON is 10 Gb/s. The OFDM data is generated offline by Matlab. As shown in the inset (i) of Fig. 3, the input binary data is converted from serial to parallel format and mapped into 16-quadrature amplitude modulation (16-QAM) constellation. The paralleled symbol strings are divided into two groups and each group contains the data of 16 ONUs. The subcarrier numbers of two data groups are both 128, in which 64 subcarriers are filled with data and others are set to be zero as guard band. In order to realize direct-detection optical OFDM, Hermitian symmetry is implemented in the data subcarriers to provide real numerical output data [15,16]. After 128-point IFFT, the generated OFDM data of two groups are interleaved with each other to constitute a TI-OFDM signal. A cyclic prefix of 20 samples is added for alleviating inter-symbol interference (ISI) caused by chromatic dispersion. Then the TI-OFDM signal is output by the Tektronix AWG 7122C with 10-GSa/s sampling rate and 8-bit resolution which functions as a DAC. After E/O conversion at the MZM, the optical TI-

#205194 - $15.00 USD Received 21 Jan 2014; revised 5 Mar 2014; accepted 5 Mar 2014; published 22 May 2014

OFDM signal is launched into an EDFA. A following TOF is employed to mitigate the ASE noise. Through a 25-km SSMF transmission, the downstream signal is split by a 1:32 optical splitter at the remote node. At the ONU side, a PD is used to detect the optical TI-OFDM signal and a Tektronix real-time oscilloscope (DSA 70804) at 5 GSa/s is followed to sample the electrical signal. In order to sample different data groups in the TI-OFDM signal, an electrical delay line (SHF 2000DEL WOC) is employed after PD to obtain an appropriate time delay in the experiment. In practical access networks, a controlling unit is needed to properly adjust the sampling time of the ADC chip in the ONU. With the use of sampled data, a 128-point FFT and a single-tap equalizer are implemented offline to retrieve the required data of the ONUs as shown in the inset (iii) of Fig. 3. In our experiment, we also implement the transmission of the TI-OFDM signal with four data groups, in which the FFT size and the sampling rate of ONU are reduced to 64 points and 2.5 GSa/s, respectively.

In a conventional OFDM PON, each ONU usually samples and processes the data transmitted to all the ONUs with a high sampling rate and a large FFT size to recover its required information data. As depicted in the insets (ii) and (iv) of Fig. 3, the sampling rate and the FFT size are 10 GSa/s and 256 points respectively for the ONUs in the conventional OFDM PON. However, by using TI-OFDM technique, each ONU only needs to process one data group in the TI-OFDM signal, thus greatly reducing the sampling rate and the FFT size of ONUs, and therefore improving the energy efficiency of ONUs for the OFDM PON.

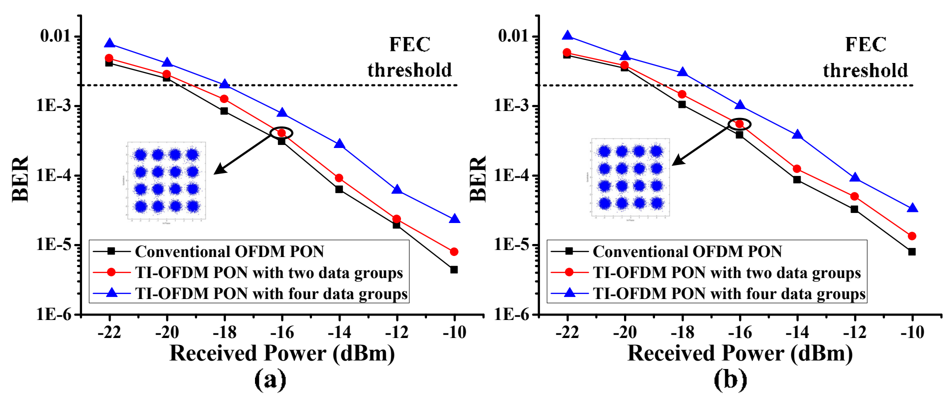

Fig. 4. BER curves of data after (a) back-to-back transmission and (b) 25-km SSMF transmission in the conventional OFDM PON and the proposed energy-efficient OFDM PON with the TI-OFDM technique, respectively.

Figures 4(a) and 4(b) show the bit error ratio (BER) curves of signals after back-to-back and 25-km fiber transmissions in the conventional OFDM PON and the proposed OFDM PON based on the TI-OFDM technique, respectively. The 25-km SSMF transmission brings about 0.8-dB power penalty at a BER level of 2×10^{-3} of forward error correction (FEC) threshold for both the conventional OFDM PON and the TI-OFDM PON. In Fig. 4(b), the receiver sensitivity at the FEC limit is about −18.7 dBm for the signal of the proposed OFDM PON with two data groups, which is a little worse than that of the conventional OFDM PON by ~0.3 dB. However, for the TI-OFDM PON with four data groups, the receiver sensitivity of the ONU is degraded by 1.2 dB compared to that in the conventional OFDM PON as shown in Fig. 4(b), which can be mainly attributed to the serious ISI induced by frequency overlapping of different data groups. Therefore, aggregating all the downlink broadcast data into two or four data groups can effectively reduce the energy consumption of ONUs in the practice network as long as the access system has a little power margin.

#205194 - $15.00 USD Received 21 Jan 2014; revised 5 Mar 2014; accepted 5 Mar 2014; published 22 May 2014

4. Numerical analysis for energy efficiency

In order to quantitatively analyze the energy efficiency of ONUs, we investigate an OFDM PON supporting 32 ONUs based on the TI-OFDM technique. The total power consumption of devices in each ONU in a 10-Gb/s conventional OFDM PON is estimated to be 3.5 W, in which the ADC/DSP chip dissipates about 1.5 W according to the data provided in Ref [7,12,17]. Here, we only consider the variation of power consumed by the ADC/DSP chip. Denote P(1), P(2), and P(4) as the power consumptions of the ADC/DSP chip when it operates in the conventional OFDM PON and the proposed OFDM PON with two and four data groups. Assume P(1): P(2): P(4) = 1: 1/2: 1/4. We also define offered load as the ratio of current traffic volume over the maximum system-supported capacity in the OFDM PON. At the OLT, the downlink data is firstly divided into two groups and each group contains the data of 16 ONUs. Only if the offered loads of the two data groups are both lower than 50%, the TI-OFDM technique with two groups can be applied in the access network. Thus, the power consumption of the ADC/DSP chip is reduced from P(1) to P(2) for all 32 ONUs. Similarly, the TI-OFDM signal with four data groups can be used in the OFDM PON when the offered loads of four groups are all lower than 25%. In this case, the power dissipation of each ONU is decreased from P(1) to P(4). If both two conditions cannot be satisfied, the conventional OFDM signal with one data group is employed in the OFDM PON. For convenience, we define the OFDM PON that can aggregate the downstream data into one or two groups as TI-OFDM PON_1, and the one that can divide the data into one, two or four groups as TI-OFDM PON_2. Here, we use the numerical analysis model and premises in Ref [10]. to calculate the power consumptions of ONUs in the proposed TI-OFDM $PON_{1,2}$. In this model, the current traffic speed (r) of each ONU obeys a normal distribution N(R, σ), where R is the offered load and σ is the variance of the traffic of customers. Sleep mode mechanism is also applied in our analysis, i.e., the ADC/DSP chip is powered off when $r \le 0$. Figure 5(a) shows the calculated mathematical expectations of the total power consumptions of ONUs with the variation of the offered load in the conventional OFDM PON and the proposed TI-OFDM $PON_{1,2}$. It is clearly observed that the power consumption of ONUs is effectively reduced in the OFDM PON by using the proposed TI-OFDM technique compared to the conventional OFDM PON. Moreover, with the increase of the number of the data groups, the power consumption of ONUs is dramatically decreased at the cost of the degradation of the system performance. Therefore, a trade-off between the energy efficiency and the network performance should be carefully considered in the practical access network. Figure 5(b) depicts the network traffic in the course of an average day in the fixed access networks of North America [18], which indicates that the traffic demands from end users fluctuate over the time. Based on the data presented in Fig. 5(b), we provide the calculated power consumption of ONUs versus time in different OFDM PONs in Fig. 5(c). In the conventional OFDM PON, the energy consumption of ONUs in an average day is about 2.55 kW·h. However, by using the TI-OFDM technique, the energy dissipation of ONUs is about 2.11 kW·h and 1.87 kW·h in the TI-OFDM PON_1 and TI-OFDM PON_2, respectively. Therefore, compared to the conventional OFDM PON, energy savings of 17.1% and 26.7% are achieved in the ONUs for the energy-efficient TI-OFDM $PON_{1,2}$, respectively.

#205194 - $15.00 USD Received 21 Jan 2014; revised 5 Mar 2014; accepted 5 Mar 2014; published 22 May 2014

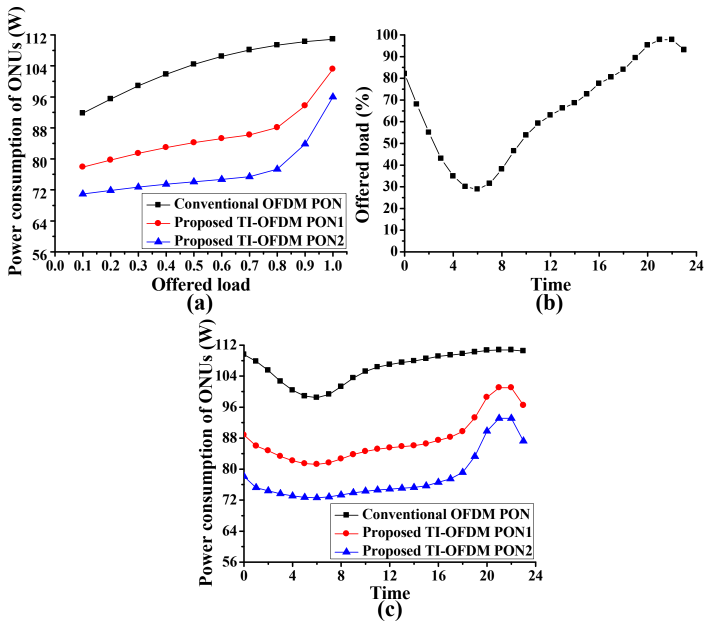

Fig. 5. (a) Calculated mathematical expectations of the power consumptions of ONUs with the variation of the offered load in the conventional OFDM PON and the proposed TI-OFDM $PON_{1,2}$; (b) Offered load over the course of an average day in North America [18]; (c) Power consumption of ONUs in the energy-efficient and conventional OFDM PONs versus time in an average day.

5. Conclusion

We have proposed a scheme to improve the energy efficiency of ONUs in the OFDM PON using the TI-OFDM technique. A proof-of-concept experiment is conducted to halve and quarter the sampling rate and the FFT size of ONUs, validating the feasibility of the proposed scheme. Numerical analysis shows that up to 26.7% of energy dissipated in the ONUs can be reduced by exploiting our proposal.

Acknowledgments

This work was supported in part by NSFC (61125504), 863 High-Tech program (2013AA013402), and Minhang Talent Program.

#205194 - $15.00 USD Received 21 Jan 2014; revised 5 Mar 2014; accepted 5 Mar 2014; published 22 May 2014