Energy-efficient Optical Network Units with Simplified FFT Operation in Direct-detection OFDM PON

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Abstract: We propose and experimentally demonstrate simplified FFT operation to improve the energy efficiency of ONUs in OFDM PON. Our proposal can achieve an energy saving of 14.6% compared to the conventional OFDM PON.
OCIS codes: (060.2330) Fiber optics communications; (060.4250) Networks.

1. Introduction

With the exponential increase of data traffic and user number, the energy dissipated by passive optical networks (PONs) is growing quickly in recent years, resulting in a high operational cost for operators. Generally, the access networks are engineered for satisfying the peak traffic demands from customers. Therefore, the PON system exhibits low energy efficiency when the network capacity is not fully utilized during non-peak hours of a day [1]. In literatures, a number of approaches have been reported to improve the energy efficiency of various PON systems, including time division multiplexing (TDM) PON [2], wavelength division multiplexing (WDM) PON [3], and orthogonal frequency division multiplexing (OFDM) PON [4].

Owing to its high spectral efficiency and robust dispersion tolerance, OFDM PON has been considered to be a promising candidate for next-generation access networks [5]. However, OFDM PON is an energy-hungry system since the generation and demodulation of electrical OFDM signals require high-speed analog-to-digital converters/digital-to-analog converters (ADCs/DACs) and digital signal processing (DSP) chips [6-7]. Nonetheless, the reduction of the energy consumption of optical network units (ONUs) has not been considered, which accounts for ~80% of the total energy dissipated by OFDM PONs.

In this paper, we propose and experimentally demonstrate a simplified FFT technique to improve the energy efficiency of ONUs in a direct-detection OFDM PON. In our scheme, the downstream data is adaptively loaded onto the first one of every *m* OFDM subcarriers when the bandwidth requirement of end users is low. At the ONU, the FFT size can be simplified by *m* times to recover the required data, effectively reducing the computation amount of DSP chips. Thus, our proposal can save the energy consumption of ONUs in the OFDM PON during low-load hours of a day. Numerical analysis of a practical instance shows that 14.6% energy saving of DSP chips in the ONUs can be achieved by using our proposed scheme compared to a conventional OFDM PON.

2. Operation Principle

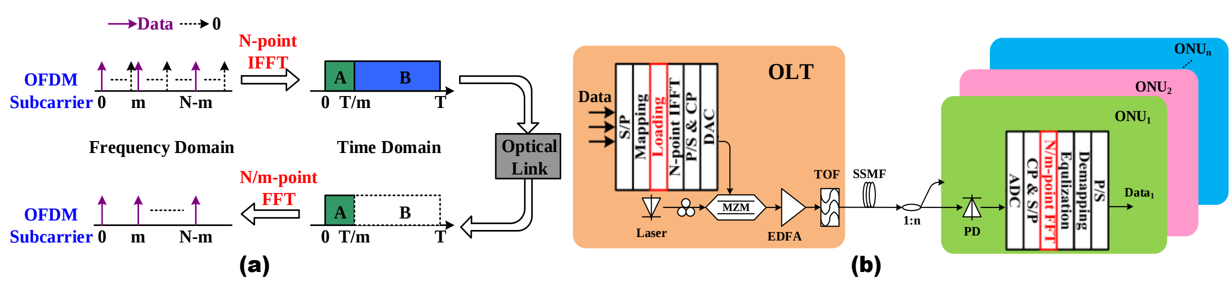

Fig. 1. (a) Basic principle of the simplified FFT technique. (b) Schematic diagram of the proposed energy-efficient ONUs by using the simplified FFT technique in the OFDM PON.

The basic principle of the simplified FFT technique is depicted in Fig. 1(a). It is known that an OFDM signal is generated and demodulated by IFFT/FFT operation in DSP chips, which can be simply given by [8]

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) \exp\left(\frac{j2\pi nk}{N}\right) \qquad for \quad 0 \le n \le N-1 \tag{1}$$

and

$$X(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x(n) \exp\left(\frac{-j2\pi nk}{N}\right) \qquad for \quad 0 \le k \le N-1 \tag{2}$$

where *X(k)* and *x(n)* are the frequency-domain and time-domain signals, respectively. When the bandwidth requirement from end users is low in the OFDM PON, only the first subcarrier in every *m* OFDM subcarriers

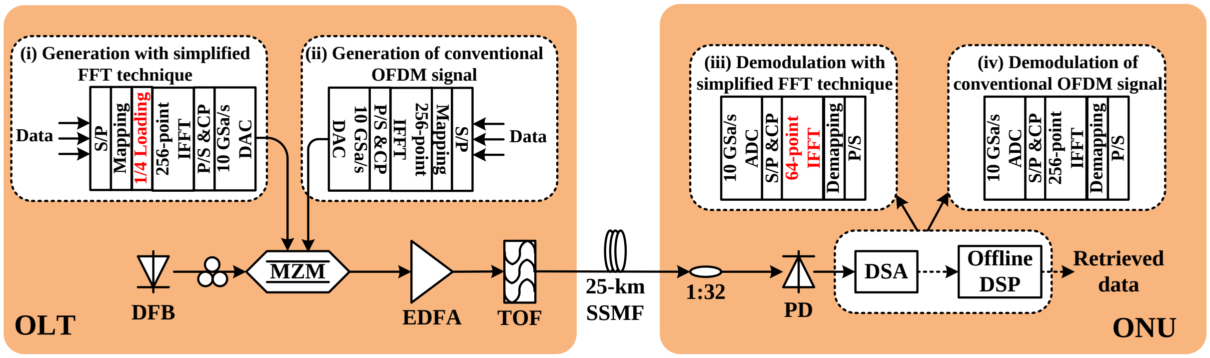

Fig. 2.Experimental setup of the proposed energy-efficient ONUs in the OFDM PON based on the simplified FFT technique.

is loaded with data and the others are all set to be zero. Therefore, the OFDM signal generated by IFFT can be expressed as:

$$x(n)=\frac{1}{\sqrt{N}}\sum_{k'=0}^{N/m-1}Y(k')\exp\left(\frac{j2\pi nk'}{N/m}\right)\quad for\ \ 0\le n\le N-1 \tag{3}$$

where $Y(k')$ meets the relationship of $Y(k')=X(mk')$, for $0\le k'\le N/m-1$. From the equation, it is easily observed that $x(n+k'm)$ is equal to $x(n)$ for $0\le n\le m-1$ and $0\le k'\le N/m-1$, i.e., the data in the block B of the optical-domain signal of Fig. 1(a) is the repetition of the data in the block A. We define $y(n')=x(n')$ for $0\le n'\le N/m-1$. Thus, $y(n')$ and $Y(k')$ satisfy the IFFT equation:

$$y(n')=\frac{1}{\sqrt{N}}\sum_{k'=0}^{N/m-1}Y(k')\exp\left(\frac{j2\pi n'k'}{N/m}\right)\quad for\ \ 0\le n'\le N/m-1 \tag{4}$$

At the receiver, only the first N/m sampled data of the OFDM frame are selected and others are discarded. With N/m-point FFT operation, the data carried by the OFDM subcarriers can be retrieved from the time-domain signal by the equation:

$$Y(k')=\frac{m}{\sqrt{N}}\sum_{n'=0}^{N/m-1}y(n')\exp\left(\frac{-j2\pi n'k'}{N/m}\right)\quad for\ \ 0\le k'\le N/m-1 \tag{5}$$

Figure 1(b) illustrates the schematic diagram of the proposed energy-efficient OFDM PON based on the simplified FFT technique. The generation of OFDM signal has been described in detail in Fig. 1(b). We define a parameter C as the total transmission capacity of the OFDM PON. When the current network traffic is lower than C/m, only the first subcarrier in every m OFDM subcarriers is loaded with data. Hermitian symmetry is performed in the input data vector for IFFT operation to realize the direct-detection OFDM system. Based on the simplified FFT technique described in Fig. 1(a), the signal processing in each ONU is implemented with only the first N/m sampled points. After converting from serial to parallel format and removing cyclic prefix, the sampled data is processed by N/m-point FFT and corrected by an equalizer to retrieve the required data. Conventionally, each ONU in the OFDM PON has to process the downlink OFDM signal with a FFT size of N points regardless of the current traffic condition. However, by using our proposed scheme, the FFT size in the DSP chip of the ONU is greatly reduced during low-load hours. As the energy consumption of the DSP chip accounts for a portion of the total energy consumption of the ONU, the reduction of the computation amount in the DSP chip can improve the energy efficiency of ONUs in the OFDM PON.

3. Experimental Setup and Results

Figure 2 shows the proof-of-concept experimental setup of the OFDM PON with energy-efficient ONUs based on the simplified FFT technique. Firstly, the input binary data is converted from serial to parallel format. The total number of OFDM subcarriers is 256. When traffic requirement from end users becomes low, some data subcarriers can be set to zero accordingly. We assume that the current network traffic is one quarter of the maximum network capacity. In a conventional OFDM PON, the 96^{th}~127^{th} & 129^{th}~160^{th} subcarriers are usually selected to load data. However, in our proposed scheme, the data are assigned onto the OFDM subcarriers according to the approach provided in Fig. 1(a). The data occupy the $4a^{th}$ OFDM subcarriers for $1\le a\le 63$. The OFDM data is output by an arbitrary waveform generator (AWG). Through 25-km fiber transmission, the optical OFDM signal is split by a 1:32 optical splitter and individually routed to the ONUs by the distribution fibers. At the ONU, a PD with a 3-dB bandwidth of 10 GHz is employed to detect the optical OFDM signal. For the conventional OFDM PON, an FFT operation with a size of 256 points has to be implemented to obtain the data. Thus, by using our proposed method, the computation amount of DSP chip in the ONU can be reduced by 4 times, resulting in a large reduction of the energy consumption of ONUs in the OFDM PON. Figures 3(a) and 3(b) respectively 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

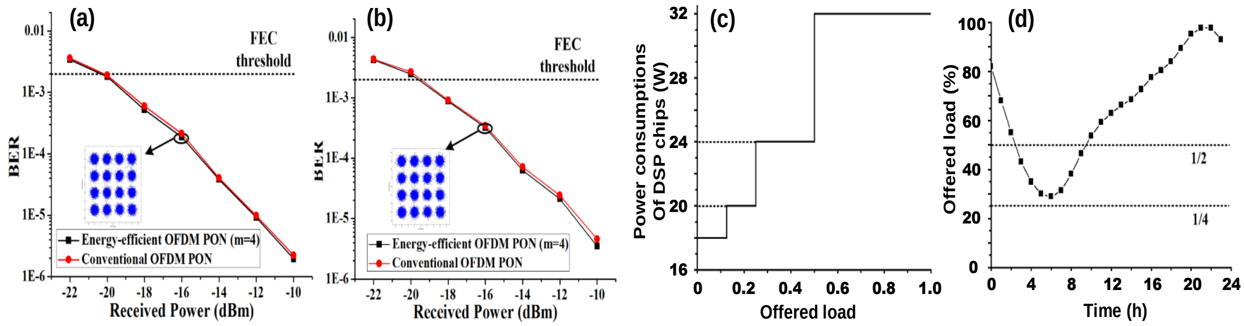

Fig. 3.BER curves and constellations of signals after (a) back-to-back and (b) 25-km fiber transmissions in the conventional and energy-efficient OFDM PONs, respectively. (c) Power consumption of DSP chips of ONUs with the variation of the offered load in the proposed OFDM PON; (d) Offered load over the course of an average day in North America [9].

proposed OFDM PON based on the simplified FFT technique. Corresponding constellations of the 16QAM signals in the energy-efficient OFDM PON are provided at a received power of -16 dBm. The 25-km SSMF transmission brings about 0.6-dB power penalty at a BER level of 2×10^{-3} of forward error correction (FEC) threshold for both conventional OFDM PON and energy-efficient OFDM PON. In Fig. 3(b), the receiver sensitivity at the FEC limit is about -19.6 dBm for the signal of the proposed OFDM PON, which is almost the same as that in the conventional OFDM PON. Therefore, the simplified FFT technique can be used to effectively reduce the energy consumption of ONUs in the OFDM PON while maintaining the system performance.

In order to quantitatively analyze the energy efficiency of ONUs, we investigate an OFDM PON supporting 32 ONUs based on the simplified FFT technique. In a conventional OFDM PON, the power consumption of the DSP chip in each ONU is estimated to 1 W according to the data provided in Ref. [6-7]. Therefore, the total power consumption of the DSP chips in the ONUs is 32 W. It is assumed that the power consumption of the DSP chip decreases to 1/m W when the FFT size becomes *N/m* points. We define offered load as the ratio of current traffic volume to the maximum system-supported capacity in the OFDM PON. Figure 3(c) depicts the power consumption of the DPS chips in the ONUs with the variation of offered load in the proposed OFDM PON. When the offered load is lower than 0.5, the data transmitted to ONUs are allocated to the even OFDM subcarriers. Thus, the receiver at the ONU side can retrieve the required data with a 128-point FFT operation. So the total power consumption of the DSP chips of ONUs is reduced to 16 W. Similarly, the FFT size of the DSP chip in the ONUs decreases to 64 and 32 points while the offered load is lower than 0.25 and 0.125, respectively. The corresponding power consumption of DSP chips is 8 W and 4 W in the ONUs. Figure 3(d) plots the offered load over the course of an average data in North America [9]. In Fig. 3(d), the offered load is lower than 0.5 from 3 AM to 9 AM. Therefore, the total energy consumption of the DSP chips in the energy-efficient ONUs is about 0.656 kw ħ in an average day. Nonetheless, in a conventional OFDM PON, the DSP chip in the ONUs has to process the downlink OFDM signal with a FFT size of 256 points all the time, resulting in an overall energy consumption of 0.768 kw ħ. Thus, the energy-efficient OFDM PON based on the simplified FFT technique can achieve an energy saving of 14.6% compared to the conventional OFDM PON.

4. Conclusions

We have proposed and experimentally demonstrated an OFDM PON system with energy-efficient ONUs based on the simplified FFT technology. By using our proposed scheme, the computation amount of the DSP chip in each ONU is reduced by 4 times when the current network traffic is about 5 Gb/s. Numerical analysis shows that up to 14.6% energy consumed by the DSP chips of ONUs can be saved by using our proposal in the OFDM PON.

5. Acknowledgements

This work was supported in part by NSFC (61125504) and 863 High-Tech program (2013AA013402/2015AA015503).

6. References

[1] K. J. Christensen, et al, Comput. Commun., 27 (2004) p. 1758.
[2] C. Van Praet, et al, Electron. Lett., 48 (2012), p. 1361.
[3] K. Tse, et al, in Proc. OFC/NFOEC 2011, paper OThB6.
[4] H. Kimura, et al, Photo. Technol. Lett., 24(2012), p. 2132.
[5] N. Cvijetic, et al, J. Lightw. Technol., 30(2012), p. 384.
[6] B. Sedighi, et al, in Proc. OFC/NFOEC 2012,paper JTh2A.
[7] B. Skubic et al, Commun. Mag., 50(2013), p. 122.
[8] J. Armstrong, et al, J. Lightw. Technol., 27(2009), p. 189.
[9] Sandvine, http://www.sandvine.com/news/global_broadband_trends.asp.