High-capacity and low-cost long-reach OFDMA PON based on distance-adaptive bandwidth allocation

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Abstract: We propose and experimentally demonstrate a distance-adaptive bandwidth allocation scheme to realize high-capacity long-reach orthogonal frequency division multiple access passive optical network (OFDMA PON) with cost-effective electro-absorption modulator (EAM). In our scheme, the subcarriers in downstream OFDM signal are properly allocated to the optical network units (ONUs) with different fiber transmission lengths. By this means, the detrimental influence of power fading induced by dispersion and chirp can be avoided, thus all OFDM subcarriers can be modulated with high-order quadrature amplitude modulation (QAM) format, leading to a high transmission capacity. A proof-of-concept experiment is performed, in which three ONUs with transmission distances of 25, 50, and 100 km are assigned with different subcarriers, respectively. By using distance-adaptive bandwidth allocation technique, an OFDM signal of 34.5 Gb/s is successfully delivered to the ONUs with a bit error ratio (BER) lower than 2×10^{-3}.

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

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1. Introduction

Driven by the exponentially increasing customer demands for broadband services, passive optical network (PON) has emerged as a promising candidate to economically provide high bandwidth to end-users [1,2]. Recently, in order to satisfy the requirements of next-generation access networks, such as high capacity, high split-ratio, and long transmission distance, long-reach PON has been proposed and extensively studied by researchers [3–6]. By consolidating the optical metro and access networks, the long-reach PON can effectively reduce the number of electronic interfaces and hence capital and operational cost. In addition, the hierarchies of optical network can be greatly simplified by the long-reach PON, reducing network latency and thus benefiting real-time broadband services. Multiple schemes, such as time division multiplexing (TDM) [5], wavelength division multiplexing (WDM) [7], and orthogonal frequency division multiplexing (OFDM) [8–12], have been used in the long-reach PON to support a large number of customers with a broad coverage. Among these schemes, optical OFDM modulation is a promising solution due to its high spectral efficiency, robust dispersion tolerance, and flexible bandwidth allocation [13].

To further reduce the cost and simplify the system, intensity modulation-direct detection (IM-DD) is desired for the long-reach OFDMA PON. In recent years, cost-effective transmitters, such as directly-modulated laser (DML) and electro-absorption modulated laser (EML), have been employed to realize IM-DD OFDM systems [9,14]. However, the OFDM signal generated by these transmitters is a double-sideband (DSB) signal, which results in detrimental dispersion- and chirp-related power fading. It was reported that the 3-dB bandwidth of 100-km DSB-OFDM transmission system is limited to about 4 GHz [9]. Therefore, many efforts were dedicated to mitigating the effect induced by power fading [15–18]. It has been proposed that modifying the chirp parameter of DMLs or EMLs to be negative or replacing the deployed fibers by the negative-dispersion fibers can increase available transmission bandwidth [15,16]. Besides, suppressing one sideband of the DSB signal with a dual EML scheme is also a way to minimize the influence of power fading [17,18]. However, these schemes are relatively expensive and complex to be implemented in practical access networks.

In this paper, we propose and experimentally demonstrate a distance-adaptive bandwidth allocation scheme to realize high-capacity and low-cost long-reach OFDMA PON. In our scheme, the frequency response of the electro-absorption modulator (EAM)-based OFDM system is measured over different fiber transmission lengths. Due to the power fading caused by the dispersion of the fiber and the chirp of the EAM, the available bandwidths for the end-users with diverse fiber distances are different. Then, the whole bandwidth of the OFDM transmitter is split into several bands, which are properly allocated to different optical network units (ONUs). By this means, the unavailable bandwidth for one ONU can be used to transmit data for other ONUs, thus fully utilizing the limited bandwidth of the long-reach OFDMA PON. Moreover, the channels for the ONUs in the access network are fixed and the bandwidth allocation scheme can remain the same while the system operates. Therefore, by appropriately defining the priorities of the OFDM bands for the ONUs, the proposed scheme does not introduce much complexity in the long-reach OFDMA PON system. Compared to the previous works, our proposal exhibits the advantages of low cost, easy implementation, and low complexity.

2. Operation principle

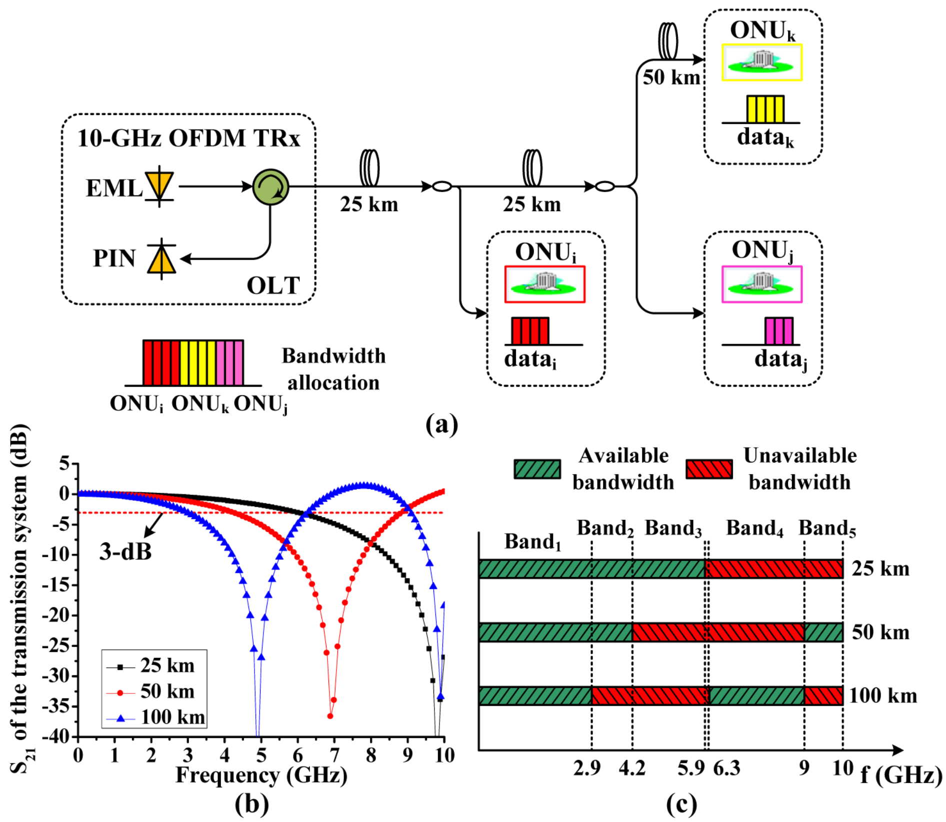

Fig. 1. (a) Schematic diagram of the proposed long-reach OFDMA PON based on distance-adaptive bandwidth allocation; (b) Frequency responses of ONUs with different transmission lengths; (c) Principle of distance-adaptive bandwidth allocation scheme.

The schematic diagram of the proposed long-reach OFDMA PON based on distance-adaptive bandwidth allocation is depicted in Fig. 1(a). Since the practical long-reach PON usually serves a large number of end-users within a broad area, the fiber lengths between optical line terminal (OLT) and each ONU are different, varying from 0 to 100 km. When implementing IM-DD OFDM with EML or DML, the OFDM signal is inevitably affected by the power fading caused by the fiber dispersion and the laser chirp. With the variation of the fiber transmission lengths, the frequency response of the long-reach PON system would change accordingly. Considering small-signal approximation, the power loss due to power fading at the end of transmissions can be given as [9,19]

$$(1+\alpha^2)\cos^2(2\pi^2\beta_2 Lf^2-\tan^{-1}\alpha) \tag{1}$$

where α is the chirp parameter of the EML or DML, β_2 is the group velocity dispersion (GVD) parameter, L is the fiber length, and f is the frequency of an electrical OFDM subcarrier. The OFDM subcarriers suffer serious power fading when $\left|2\pi^2\beta_2 Lf^2-\tan^{-1}\alpha\right|$ approaches 0.5π.

The frequency responses of the long-reach OFDMA PON system with different transmission distances are plotted in Fig. 1(b), where the bandwidth is 10 GHz and the chirp parameter is assumed to be 0.6 for a typical EML. A 3-dB threshold is used as the criteria to determine which frequency bands could carry data. As shown in Fig. 1(c), the available bandwidths for the ONUs with 25-km, 50-km, and 100-km fiber lengths are 0~5.9 GHz, 0~4.2 & 9~10 GHz, and 0~2.9 & 6.3~9 GHz, respectively. Here, we define $\text{Band}_{1\sim5}$ as the frequency bands of 0~2.9, 2.9~4.2, 4.2~5.9, 6.3~9, and 9~10 GHz, respectively. From the figure, it is clearly observed that the ONUs with a certain fiber length cannot make full use of the 10-GHz bandwidth of the OFDMA PON. In a conventional long-reach OFDMA PON, only Band_1 is utilized to transmit data since it is available for all the ONUs, severely limiting the network capacity. To improve the bandwidth utilization of access networks, the five frequency bands are properly allocated to ONUs with different transmission distances in our proposed scheme. In Fig. 1(c), Band_3 is only available for the ONUs with 25-km fiber transmission. Thus, these ONUs should firstly employ Band_3, rather than Band_1 and Band_2, to deliver data. Similarly, Band_4 and Band_5 are used with the highest priority to transmit data of the ONUs with 100-km and 50-km fiber lengths, respectively. For Band_2, the ONUs with 25-km and 50-km fiber lengths have the second priority to employ them to deliver data. Lastly, Band_1 should be reserved until other available bands are fully occupied. By appropriately allocating bandwidth to the ONUs with different fiber lengths, the detrimental influence of power fading in the DSB-OFDM system can be effectively alleviated and thus the transmission capacity of the long-reach OFDMA PON can be maximized.

3. Experimental setup and results

We perform a proof-of-concept experiment to verify the feasibility of the proposed long-reach OFDMA PON based on the distance-adaptive bandwidth allocation. The experimental setup is illustrated in Fig. 2. At the OLT, a continuous wave (CW) light from a tunable laser at 1550 nm is fed into a 10-GHz EAM, which is driven by an electrical OFDM signal. Here, the tunable laser and the EAM are employed to emulate an EML. The linear electrical-to-optical (E/O) conversion region of the EAM is between −1.0 V and −0.4 V. In the experiment, the bias voltage of the EAM is set to be −0.7 V, which is about the center of the linear E/O conversion region. With this bias voltage, the chirp parameter is measured to be 0.60 for the EAM-based OFDM system [20]. The OFDM data is generated offline by Matlab. The total number of data subcarriers is 256 and 16-QAM symbols are mapped onto these subcarriers. After 512-point IFFT operation, a cyclic prefix of 1/16 is added to alleviate the inter-symbol interference incurred by chromatic dispersion. An arbitrary waveform generator (AWG) (Tektronix 7122C) outputs the OFDM data with 20-GSa/s sampling rate and 8-bit resolution. Therefore, the OFDM signal has a bit rate of ~34.5 Gb/s, which can be simply obtained by the

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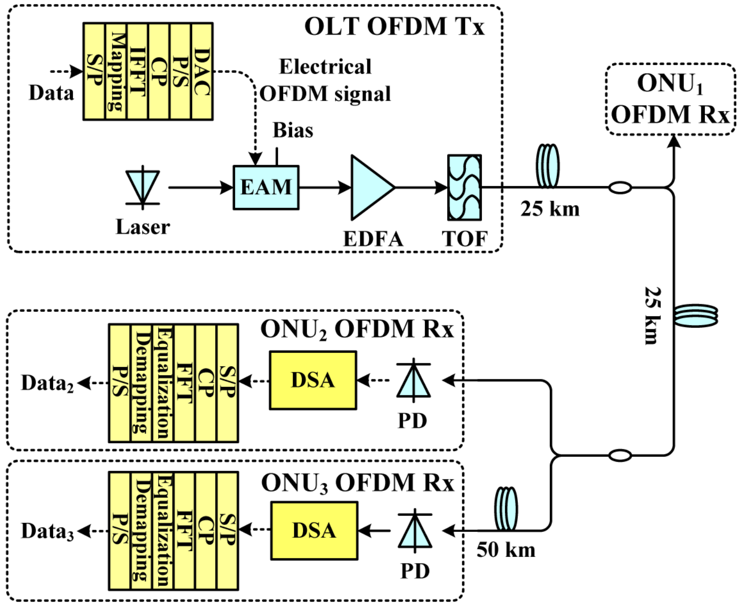

Fig. 2. Experimental setup of the proposed long-reach OFDMA PON based on the distance-adaptive bandwidth allocation scheme.

equation [21]

$$R \approx \frac{1}{(1+\varepsilon_{Training})(1+\varepsilon_{Cyclic})(1+\varepsilon_{FEC})} \times \frac{n}{N} \times Sa \times M \ Gb/s \tag{2}$$

where $\varepsilon_{Training}$, ε_{Cyclic}, and ε_{FEC} are the overheads induced by training symbol, cyclic prefix, and forward error correction (FEC), n and N are the numbers of OFDM data subcarriers and IFFT points, Sa is the sampling rate of the AWG, and M is the number of bits per symbol. Here, $\varepsilon_{Training}$, ε_{Cyclic}, and ε_{FEC} are 0.02, 0.0625, and 0.07, respectively. An erbium doped fiber amplifier (EDFA) is employed to compensate for the transmission loss and a tunable optical filter (TOF) is used to mitigate amplified spontaneous emission (ASE) noise. At the output port of OLT, the optical OFDM signal with a power of 10.5 dBm is launched into a standard single mode fiber (SSMF). To evaluate the transmission performances of the ONUs

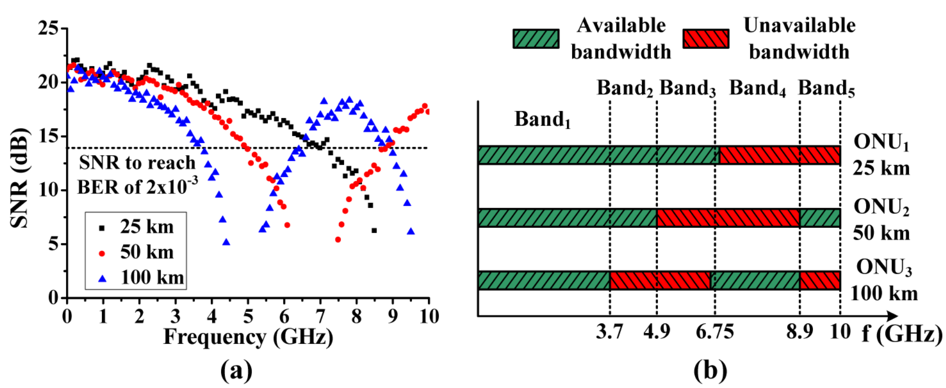

Fig. 3. (a) SNR values versus frequency in 25-km, 50-km, and 100-km EAM-based OFDM systems; (b) Distance-adaptive bandwidth allocation in the proposed long-reach OFDMA PON.

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with different transmission distances, three SSMFs with lengths of 25 km, 50 km, and 100 km are selected, which deliver data to ONU_1, ONU_2, and ONU_3, respectively. At the ONU side, another EDFA and a variable optical attenuator (VOA) are inserted before the 10-GHz photodetector (PD) to measure the bit error ratio (BER) of the received signal. After O/E conversion, the electrical OFDM signal is sampled by a real-time oscilloscope (LeCroy 806Zi-A) at 40 GSa/s. The sampled data is then down-sampled by a factor of 2. Through FFT operation, one-tap equalization, and 16-QAM symbol decoding, the data demanded by the ONUs is recovered. In addition, by selecting the required subcarriers with a bandpass filter, the processing rate of electronic devices in the ONUs can be greatly reduced, thus lowering the cost of ONUs in the OFDMA PON [22].

The SNR of each subcarrier is estimated from the constellation of the received OFDM signal [23,24]. Figure 3(a) gives the SNR values with the variation of frequency in the ONUs with 25-km, 50-km, and 100-km fiber lengths. It is clearly observed that the power fading induced by the chirp and the dispersion affects the frequency response of the system as discussed in Section II. The FEC threshold is set to be 14 dB to achieve a BER of 2×10^{-3} for 16-QAM OFDM signal. Obviously, ONU_2 and ONU_3 both have two available bands, 0~4.9 GHz & 8.9~10 GHz and 0~3.7 GHz & 6.6~8.9 GHz, while ONU_1 has a passband of 0~6.9 GHz. For a conventional long-reach OFDMA PON, only the low frequency band of 0~3.7 GHz would be used to deliver data since it is available for all the ONUs. Figure 3(b) gives the strategy of our proposed distance-adaptive bandwidth allocation, which divides the 10-GHz bandwidth into five bands, i.e., 0~3.7 GHz, 3.7~4.9 GHz, 4.9~6.75 GHz, 6.75~8.9 GHz, and 8.9~10 GHz. The corresponding OFDM subcarriers for the five bands are the 0th~93th, 94th~123th, 124th~169th, 170th~223th, and 224th~255th subcarriers, respectively. The total available bandwidth is about 6.75 GHz, 6 GHz, and 5.85 GHz for ONU_1, ONU_2 and ONU_3, respectively. Due to the destructive interference caused by power fading, $Band_4$ is unavailable for ONU_1 and ONU_2. However, with the increase of fiber length, it becomes useable for ONU_3 as depicted in Fig. 3(b). Thus, $Band_4$ should be utilized by ONU_3 with the highest priority. Similarly, $Band_3$ and $Band_5$ must be firstly allocated to ONU_1 and ONU_2, respectively. Since it can be used by two ONUs, $Band_2$ has a relatively lower priority than $Band_3$ and $Band_5$ to deliver data for ONU_1 and ONU_2. As for $Band_1$, it should be reserved for three ONUs until other available bands are all occupied. The priorities of the five bands are provided in Table 1 for the three ONUs with different transmission distances. By using the distance-adaptive bandwidth allocation scheme, the 10-GHz bandwidth of OFDMA PON can be fully utilized, effectively mitigating the detrimental influence incurred by power fading and maximizing the transmission capacity of the access network. Compared to the conventional

Table 1. Priority level of $Band_{1\sim5}$, available bandwidth, and data rate for the $ONU_{1\sim3}$, conventional OFDMA PON, and the proposed scheme (√: Applicable; N/A: Not Applicable; C-OFDMA PON: Conventional OFDMA PON)

Priority Level	$Band_1$	$Band_2$	$Band_3$	$Band_4$	$Band_5$	Bandwidth (GHz)	Data Rate (Gbps)
ONU_1 (25 km)	Low	Medium	High	N/A	N/A	6.75	23.3
ONU_2 (50 km)	Low	Medium	N/A	N/A	High	6	20.7
ONU_3 (100 km)	Low	N/A	N/A	High	N/A	5.85	20.2
C-OFDMA PON	√	N/A	N/A	N/A	N/A	3.7	12.8
Proposed Scheme	√	√	√	√	√	10	34.5

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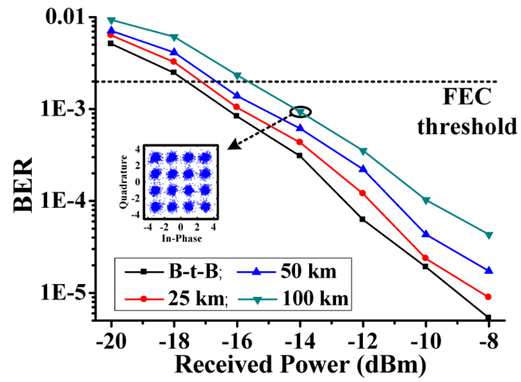

Fig. 4. BER curves of OFDM signals after back-to-back, 25-km, 50-km, and 100-km SSMF transmissions in the proposed long-reach OFDMA PON.

OFDMA PON, the network capacity increases from 12.8 Gb/s to 34.5 Gb/s in our proposed long-reach OFDMA PON. It is worth noting that the maximum data rates of $ONU_{1\sim3}$ are 23.3 Gb/s, 20.7 Gb/s, and 20.2 Gb/s, respectively. Besides, in practical access networks, the channel bandwidth should be properly allocated according to the actual distances of ONUs, and bit loading technique can be employed to further increase the transmission capacity [25].

Figure 4 shows the BER curves of OFDM signals after back-to-back, 25-km, 50-km, and 100-km SSMF transmissions in the proposed long-reach OFDMA PON. All the ONUs transmit data by using the available bands given in Fig. 3(b). The power penalties are about 0.46 dB, 0.92 dB, and 1.87 dB for the three ONUs with 25-km, 50-km, and 100-km fiber distances, respectively. With a launched optical power of 10.5 dBm at the OLT, the power budget of the long-reach OFDMA PON is ~26.3 dB, achieving error-free transmissions for all the ONUs after FEC correction. The corresponding constellation of the 16-QAM signal in ONU_3 is provided in the inset of Fig. 4.

4. Conclusion

We have proposed and demonstrated a long-reach OFDMA PON based on distance-adaptive bandwidth allocation. In our scheme, ONUs have different priorities to utilize different OFDM bands according to the fiber transmission lengths, thus mitigating the power fading effect in DSB-OFDM signals and maximizing the transmission capacity of the OFDMA PON. A proof-of-concept experiment is conducted to transmit a downstream OFDM signal of 34.5 Gb/s to three ONUs with 25-km, 50-km, and 100-km SSMFs by using distance-adaptive bandwidth allocation technique. Experimental results show that our proposal could be a promising solution to realize high-capacity and low-cost long-reach OFDMA PON.

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