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Power efficient and colorless PON upstream system using asymmetric clipping optical OFDM and TDMA technologies

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ABSTRACT

Asymmetric clipping optical orthogonal frequency division multiplexing (ACO-OFDM) based time division multiple access (TDMA) Passive Optical Network (PON) upstream transmission architecture is proposed. The system features low power consumption, colorless, and cost effectiveness. Performance and validity of 10 Gb/s upstream transmission are studied and confirmed by simulation. Performance degradation due to interference from rogue Optical Network Unit (ONU) is also studied.

1. Introduction

Driven by rapid growth of multimedia and Internet applications, bandwidth requirement of access network grows exponentially. Passive Optical network (PON), which takes advantage of high capacity and long reach of optical fiber, is a cost effective solution to satisfy ever-increasing bandwidth demand [1–3]. Currently, researchers are seeking for solutions to 10 Gb/s upstream transmission in PON [4–12], among which OFDM-PON is a promising candidate [7–12].

OFDM is a multi-carrier transmission technology; each carrier can be modulated by high order QAM, hence increasing transmission capacity. OFDM is also resistant to linear channel impairments by insertion of cyclic prefix (CP). Additionally, orthogonal frequency division multiple access is achieved by allocating specific OFDM subcarriers to individual users [8]. Enabled by high speed digital signal processing (DSP) and digital to analog converter (DAC) and analog to digital converters (ADC) technologies, optical orthogonal frequency division multiplexing (OOFDM) is possible to deliver tens or even hundreds of gigabits per second over fiber. So far, 100 Gb/s OFDMA-PON upstream and downstream have been demonstrated experimentally [7,12–13].

The upstream system proposed in [8] mandates certain laser wavelength spacing for each ONU to avoid beating noise [14]. This system is not colorless. Ref. [9–12] demonstrated colorless upstream transmission system. In order to realize colorless upstream OFDM transmission, each ONU has to use the same wavelength and optical carrier should be suppressed [11]. Therefore, centralized light source approach is adopted. That is, OLT delivers an optical carrier to each ONU. ONUs modulate upstream signal onto the optical carrier and then send back to OLT. An ONU generates carrier suppressed OFDM signal by Mach–Zehnder Modulator (MZM) biased at null point [9,11–12] or by Electro-absorption Modulator (EAM) and filtering out optical carrier [10]. The OLT can demodulate upstream signal either by coherent detection [9,11] or by heterodyne detection [10,12].

However, frequency offset and phase noise severely degrade system performance. Lasers with narrow linewidth and high frequency stability should be used. Computational burden for frequency offset and phase noise compensation algorithms are heavy. These factors increase cost of the whole PON system.

Additionally, reducing power consumption of optical access network is a consideration for network operators [15]. Ref. [15] listed a number of power saving technologies, most of which, however, belongs to protocol or MAC layer technologies. Few works sought for power efficient modulation in PON. Armstrong and Lowery proposed an energy efficient optical OFDM modulation scheme called asymmetric clipping optical OFDM (ACO-OFDM) [16].

In this paper, we propose an ACO-OFDM modulated time division multiple access (TDMA) colorless upstream transmission system. The performance of 10 Gb/s upstream system is evaluated by simulation. The rest of the paper is organized as follows. In Section 2, we review theory of ACO-OFDM and propose a way to generate ACO-OFDM signal by direct modulation laser (DML). Section 3 shows architecture of ACO-OFDM based TDMA-PON upstream transmission system. Method for frame synchronization is presented in Section 4. Next, transmission performance is studied by simulation. Simulation setup of 10 Gb/s upstream system is described in Section 5. In Section 6, we study performance degradation caused by bias offset and rogue ONU. Section 7 concludes the paper.

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2. ACO-OFDM

ACO-OFDM is proposed by [16], in which OFDM signal less than zero is clipped to zero, as shown in Fig. 1. In principle, half information is lost by the clipping. In fact, according to the analysis of [16], if only odd number subcarriers are modulated and even number subcarriers are set to zero, the clipping will not interfere odd subcarriers.

Because clipping is a nonlinear distortion, ACO-OFDM signal has large sideband, as indicated in Fig. 2. As a result, generating clipped electrical signal requires large bandwidth. To overcome this barrier, we propose a method to clip the signal by DML biased at threshold.

In ACO-OFDM system, as shown in Fig. 3, negative frequency subcarriers are set to complex conjugate of positive ones to generate real valued OFDM signal by IFFT. Among positive subcarriers, only odd subcarriers are modulated while even subcarriers are set to zero. Therefore, if IFFT/FFT size is N, at most N/4 independent subcarriers carry data. After CP insertion, parallel to serial and digital to analogue conversion, electrical OFDM signal is input to DML biased at threshold point. As a result, negative OFDM signal is clipped to zero because driving signal is below threshold of laser; only positive values are mapped to light intensity. At receiver, the optical signal is converted to electrical signal by photodetector. The subcarriers that carry data are extracted and demodulated.

Output light power and injection current of DML is related by [17]:

$$P = \begin{cases} s(i-i_{th}) & i \geq i_{th} \\ 0 & i < i_{th} \end{cases} \tag{1}$$

Where i is injection current; i_{th} is threshold current of laser; s is slope efficiency in the unit of W/A; P is output light intensity.

If modulation signal has DC bias at threshold point, the relationship between injection current and signal amplitude $d(t)$ is expressed as:

$$i = d(t) + i_{th} \tag{2}$$

Applying Eq. (2) to Eq. (1), the relationship between output power and OFDM signal is given by:

$$P = \begin{cases} sd(t) & d(t) \geq 0 \\ 0 & d(t) < 0 \end{cases} \tag{3}$$

As a result, signal less than zero is clipped so that ACO-OFDM signal is generated.

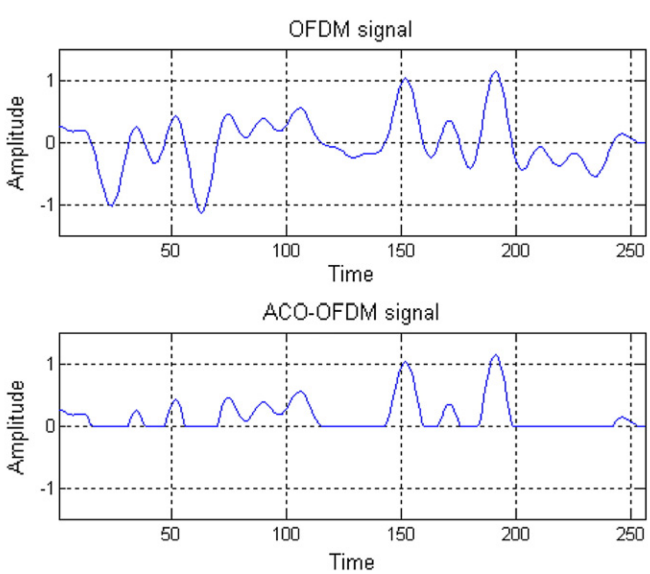

Fig. 1. Comparison of OFDM and ACO-OFDM time domain signal.

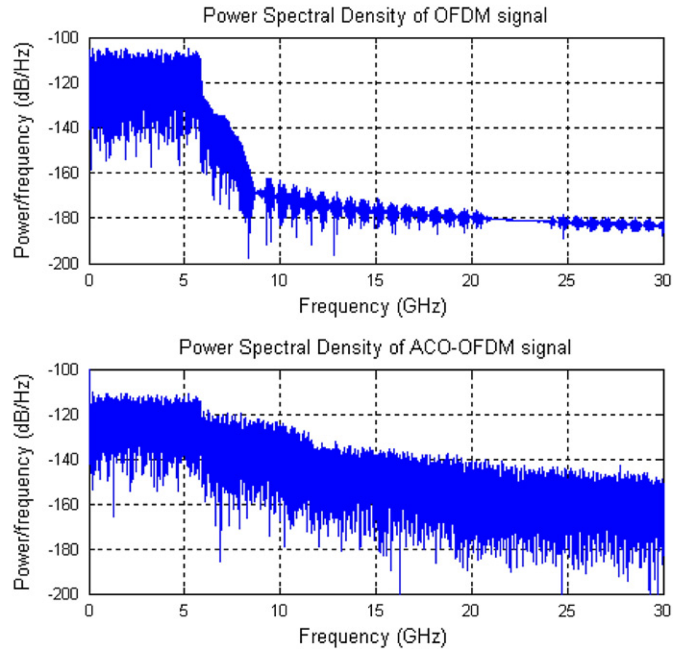

Fig. 2. Comparison of spectra of OFDM and ACO-OFDM signal.

3. ACO-OFDM based TDMA-PON upstream transmission system

In ACO-OFDM based PON system, because DML is biased at threshold point, one ONU does not emit any light unless modulation signal starts to drive the DML. TDMA is realized by allocating upstream time slot for each ONU to transmit upstream signal, as seen in Fig. 4. One ONU send a number of OFDM frames at a time, the header of OFDM frame contains preamble used for automatic gain control, frame synchronization and channel estimation.

4. Frame synchronization for ACO-OFDM

ACO-OFDM based TDMA-PON upstream receiver operates in burst mode. Receiver has to quickly synchronize with incoming signal. We propose a training sequence composed of two identical ACO-OFDM symbols for frame synchronization. Principle of the synchronization method is the same as Schmidl and Cox (SC)'s method [18]. In SC's method, one unique OFDM symbol whose first half is identical to second half is transmitted before payload symbols. Receiver searches for a symbol with two same halves to identify the start of an OFDM frame. The special symbol is generated by only modulating even number subcarriers and setting odd number subcarriers to zero. In ACO-OFDM, however, only odd number subcarriers are modulated. So, a modification to SC's method is proposed. That is, two identical ACO-OFDM symbols are transmitted as preamble. Receiver searches for two consecutive identical symbols by delayed correlation. The computational complexity of the method is similar to that of SC's method.

Mathematically, the start of a frame is n that maximize $P(n)$ given in Eq. (4).

$$P(n) = \frac{\sum_{k=0}^{N-1} (r_{n+k} r_{n+k+M})}{\sum_{k=0}^{N-1} (r_{n+k+M})^2} \tag{4}$$

Where r_n is received OFDM signal; N is the total number of subcarriers; M is OFDM symbol length including CP.