Optics Communications 380 (2016) 154–160

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Design and performance investigation of LDPC-coded upstream transmission systems in IM/DD OFDM-PONs

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ARTICLE INFO

Article history:
Received 2 March 2016
Received in revised form
18 April 2016
Accepted 23 May 2016
Available online 10 June 2016

Keywords:
IM/DD OFDM-PONs
Upstream transmission system
Interference mitigation
LDPC codes

ABSTRACT

In Intensity-Modulation Direct-Detection (IM/DD) Orthogonal Frequency Division Multiplexing Passive Optical Networks (OFDM-PONs), aside from Subcarrier-to-Subcarrier Intermixing Interferences (SSII) induced by square-law detection, the same laser frequency for data sending from Optical Network Units (ONUs) results in ONU-to-ONU Beating Interferences (OOBI) at the receiver. To mitigate those interferences, we design a Low-Density Parity Check (LDPC)-coded and spectrum-efficient upstream transmission system. A theoretical channel model is also derived, in order to analyze the detrimental factors influencing system performances. Simulation results demonstrate that the receiver sensitivity is improved 3.4 dB and 2.5 dB under QPSK and 8QAM, respectively, after 100 km Standard Single-Mode Fiber (SSMF) transmission. Furthermore, the spectrum efficiency can be improved by about 50%.

1. Introduction

The explosive growth of bandwidth-intensive services has imposed new challenges on next generation Passive Optical Networks (PONs) in terms of further lowering cost and improving transmission capacity. Recently, Orthogonal Frequency Division Multiplexing (OFDM) has attracted great research interests in PONs due to its high spectrum efficiency, flexible bandwidth provisioning and strong robustness against transmission impairments [1–5]. Cost and simplicity are key issues for the practical development of OFDM-PONs, and Intensity-Modulation Direct-Detection (IM/DD) has been demonstrated as the most cost-effective solution because it is considerably easy to install and maintain [6–8].

There have been some works focusing on the downstream transmission in IM/DD OFDM-PONs, but it will be more challenging for us to investigate upstream transmission since interferences will occur when multiple Optical Network Units (ONUs) simultaneously send their data to an Optical Line Terminal (OLT) [9–11]. More specifically, aside from Subcarrier-to-Subcarrier Intermixing Interferences (SSII) induced by square-law detection, the same laser frequency for data sending from different ONUs results in ONU-to-ONU Beating Interferences (OOBI) at the OLT receiving side. SSII and OOBI produce unwanted frequency components that may fall within the range of the desired OFDM signal spectrum, thus leading to the degradation of transmission performance. In addition, the driving signal of IM/DD systems must be a real-valued signal. To generate such signal, Discrete Multi-Tone (DMT) and Radio Frequency (RF) upconversion are two common methods [12]. However, DMT greatly reduces the spectrum efficiency since it enforces Hermitian symmetry on the input symbols of Inverse Fast Fourier Transform (IFFT). The traditional RF upconversion inserts a guard band between the optical carrier and OFDM subcarriers for the purpose of mitigating SSII, which also results in the decreased spectrum efficiency [13–17].

To mitigate SSII and increase spectrum efficiency, Vestigial-SideBand (VSB) scheme and iterative SSII cancellation were proposed in IM/DD OFDM-PONs [14]. Since the computation complexity of ONUs is rather high, symbol predistortion SSII cancellation was further designed in the OLT [15]. More interestingly, Forward Error Correction (FEC) channel coding in terms of turbo codes was utilized to mitigate the degradation of transmission performance caused by frequency selective fading and SSII [16]. However, the aforementioned studies mainly focused on the downstream transmission associated with point-to-point communication systems.

Correspondingly, we introduce Low-Density Parity Check (LDPC) codes previously used in optical communications [18,19] to our designed multipoint-to-point upstream transmission system in IM/DD OFDM-PONs, with the objective of combating SSII and OOBI. In addition, a novel radio frequency (RF) upconversion scheme is proposed for achieving the improvement of spectrum efficiency. This scheme converts the baseband OFDM single to the

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http://dx.doi.org/10.1016/j.optcom.2016.05.066
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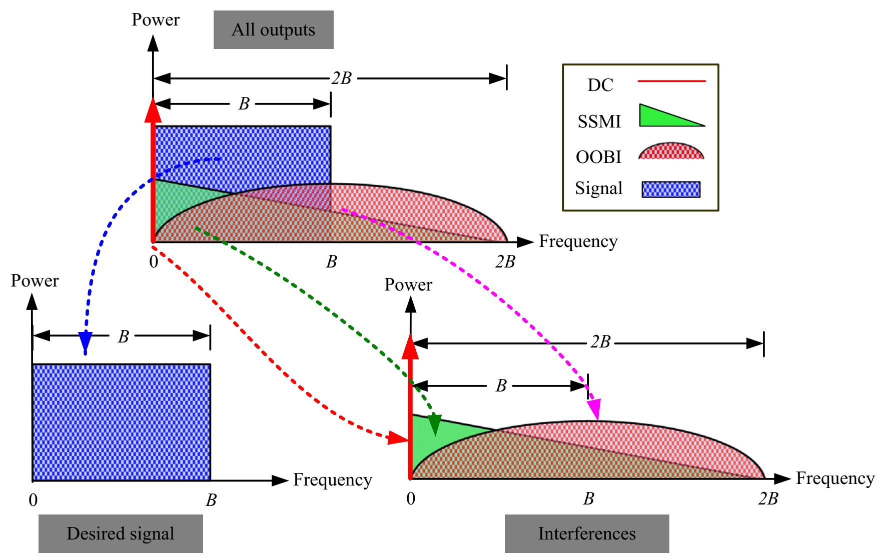

Fig. 1. Spectrum of received signals.

frequency of the signal bandwidth in positive frequency components, leaving no guard band between the optical carrier and signal subcarriers. Our contributions can be summarized as follows. 1) A novel RF upconversion scheme is proposed by us, which doubles the spectrum efficiency compared to the traditional approach. 2) A general mathematical model is derived, in order to analyze the detrimental factors (SSII and OOBI) influencing upstream transmission performance, once our RF upconversion scheme has been invoked. 3) LDPC codes are introduced within the multipoint-to-point upstream transmission system of IM/DD OFDM-PONs for the first time, in order to mitigate SSII and OOBI. Numerical simulation results indicate that the proposed system effectively combats SSII and OOBI, and then the receiver sensitivity is improved 3.4 dB and 2.5 dB under QPSK and 8QAM, respectively, after 100 km Standard Single-Mode Fiber (SSMF) transmission.

2. Mathematical model of analyzing interferences

In this section, we derive a mathematical model of analyzing the detrimental factors influencing system performance, once our RF upconversion scheme has been invoked.

In general, supposing there are L ONUs, the baseband OFDM signal of the lth ONU within one symbol period T can be expressed as in Eq. (1).

$$S_l(t) = \sum_{k=0}^{N-1} c_k^l e^{jk\Omega t}, \quad l \in [1, L], \quad t \in [0, T] \tag{1}$$

where k is the subcarrier index; N is the total number of subcarriers; c_k^l is the data symbol carried by the kth subcarrier assigned for the lth ONU; Ω is the angular frequency interval between consecutive subcarriers, and it can be computed by Eq. (2).

$$\Omega = \frac{2\pi \cdot B}{N}, \tag{2}$$

where B is the RF bandwidth of each ONU.

Next, $S_l(t)$ is upconverted to w_c ($w_c = 2\pi f_c$) for the purpose of obtaining the RF OFDM signal $S_l'(t)$ shown in Eq. (3). Note that f_c is set to $B/2$ in our upconversion method because the corresponding spectrum efficiency can raise to 100% in theory (50% for the traditional setting of 1.5B [13]).

$$S_l'(t) = \mathrm{Re}\left\{S_l(t)e^{jw_c t}\right\} = \mathrm{Re}\left\{\sum_{k=0}^{N-1} c_k^l e^{j(k\Omega + w_c)t}\right\}, \quad l \in [1, L], \quad t \in [0, T] \tag{3}$$

After being processed in an optical intensity modulator, the output optical signal of the lth ONU is given in Eq. (4).

$$E_l(t) = e^{jw_l t}\left[1 + z \cdot S_l'(t)\right] \tag{4}$$

where w_l is the frequency of the optical carrier assigned for the lth ONU, and z is the optical modulation index of an optical intensity modulator. Here, all ONUs are assumed to have the same optical carrier frequency w_0.

Therefore, after being processed in a combiner, the combined optical OFDM signal $E(t)$ can be written by Eq. (5).

$$E(t) = \sum_{l=1}^{L} E_l(t) = e^{jw_0 t} \sum_{l=1}^{L} \left[1 + z \cdot S_l'(t)\right]. \tag{5}$$

Here, the influence of optical fiber channels is ignored.

After being processed in a square-law detector, the resulting electrical signal $I(t)$ can be expressed by Eq. (6). As shown in Eq. (6), the received signal $I(t)$ consists of four terms. The first term represents the desired signal, the second term is a Direct Current (DC) component, the third term denotes SSMI, and the last term is OOBI. Given the RF bandwidth B of each ONU, we can infer that the bandwidth of SSMI and OOBI is $2B$, based on Eq. (6). Then, the spectrum of received signals is illustrated in Fig. 1. The subcarrier corresponding to the DC component is generally set to zero, in order to avoid the influence of DC components. As unwanted noise components in Fig. 1, SSMI and OOBI fall into the desired signal spectrum region, which will considerably degrade the upstream transmission performance. Accordingly, in the following section, we introduce LDPC codes to our proposed system for the achievement of improving the resistance against SSMI and OOBI.