Optical Fiber Technology 20 (2014) 309–313

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Suppression of optical beat interference-noise in orthogonal frequency division multiple access-passive optical network link using self-homodyne balanced detection

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ARTICLE INFO

Article history:
Received 27 November 2013
Revised 21 February 2014
Available online 18 April 2014

Keywords:
Balanced detection
Optical beat interference
Orthogonal frequency division multiple access
Passive optical network
Self-homodyne

ABSTRACT

A new technique, which reduces optical beat interference (OBI) noise in orthogonal frequency division multiple access-passive optical network (OFDMA-PON) links, is proposed. A self-homodyne balanced detection, which uses a single laser for the optical line terminal (OLT) as well as for the optical network unit (ONU), reduces OBI noise and also improves the signal to noise ratio (SNR) of the discrete multi-tone (DMT) signal. The proposed scheme is verified by transmitting quadrature phase shift keying (QPSK)-modulated DMT signal over a 20-km single mode fiber. The optical signal to noise ratio (OSNR), that is required for BER of 10^{-5}, is reduced by 2 dB in the balanced detection compared with a single channel due to the cancellation of OBI noise in conjunction with the local laser.

1. Introduction

In recent years, the domain of passive optical networks based on various types of orthogonal frequency division multiplexing (OFDM) techniques with high spectral efficiency has seen a rapid growth of channel capacity per access user [1,2]. It has been reported that the channel bandwidth of an OFDM based passive optical network (PON) system can be several times larger than the frequency response of optical devices that are employed in the system [3,4]. This increase is a consequence of the orthogonality of OFDM subcarriers as well as the technologies of digital signal processing (DSP) such as equalization and forward error correction. Moreover, this system is able to allocate bandwidth dynamically and have high bandwidth efficiency.

It is necessary to implement the multiple access function so that a PON using OFDM evolves into a real network as cost-effectively as possible. The number of access users should increase effectively so that the operating cost of the system goes down dramatically. An orthogonal frequency division multiple access (OFDMA) scheme is a multiple-access/multiplexing scheme that can perform a multiplexing operation of user data streams onto the downlink sub-channels and can uplink multiple access by means of uplink sub-channels. Because the modulated data streams are orthogonal to each other in the frequency domain, cross-talk between the sub-channels is eliminated. Furthermore, the dynamic bandwidth allocation within the overall OFDMA bandwidth and adaptive modulation techniques on the subcarriers makes this system flexible and efficient in terms of bandwidth usage.

However, optical beat interference (OBI) noise currently inhibits realization of the uplink scheme of an OFDMA-PON, where it is generated by the optical interference among multiple lights with the same wavelength from different access users. This interference is a problem because OFDM sub-channels are allocated dynamically to multiple access users over a single light with the same wavelength [3,5]. The technique of avoiding OBI noise using optical carrier suppression and coherent detection has been proposed [3]. However, wavelength stability is required in the optical network unit (ONU) due to the optical carrier suppression, and it is difficult to implement a cost-effective ONU because it uses a Mach–Zehnder modulator. In addition, an additional optical device such as an optical interleaver, is required to avoid the OBI effect. The technique of using an optical source with different wavelengths at each ONU has been proposed to avoid OBI noise [5]. Unfortunately, it would make the burden too heavy for the network provider because the repair and maintenance costs of the network would increase due to the inventory of different optical and electrical devices. Similarly, it is a well-known fact that the OBI noise has

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http://dx.doi.org/10.1016/j.yofte.2014.02.010
1068-5200/

been preventing the development of a subcarrier multiplexed (SCM)-PON because a SCM-PON also uses several radio frequency (RF) subcarriers over a single light with the same wavelength in order to distinguish different users [6].

In this paper, a new scheme using self-homodyne balanced detection in the optical line terminal (OLT) is proposed in order to reduce OBI noise, generated in the uplink transmission of an OFDMA-PON system. This kind of balanced detection has been proposed and used for the coherent optical communication. As far as our present knowledge goes it is the first time to utilize the self-homodyne balanced detection in order to suppress the OBI noises in OFDMA-PON system. When multiple OFDMA channels over a single optical source with the same wavelength are received simultaneously, OBI noises, produced among all OFDMA channels, are removed using balanced detection, while the intensities of the OFDMA channels are increased by 3 dB. A discrete multi-tone (DMT) modulation is utilized to generate real valued OFDM signals. The proposed technique is verified through experimental demonstration.

2. OBI-noise reduction using self homodyne balanced detection

Fig. 1 shows the concept of reducing OBI noise in an OFDMA-PON link using self-homodyne balanced detection. As shown in Fig. 1, if each ONU uses a single optical source with the same wavelength, then we can describe the OFDM signal incoming from the nth ONU as

$$E_n(t) = A_n \exp(j\omega_s t) \tag{2.1}$$

where A_n is the complex OFDM signal, An the complex amplitude of OFDM signal, and ω_s is the optical frequency. Similarly, the optical field of the local laser prepared at the balanced receiver can be written as

$$E_{LO}(t) = A_{LO} \exp(j\omega_{LO} t) \tag{2.2}$$

where A_{LO} is the constant complex amplitude and ω_{LO} is the optical frequency of the local laser. We note here that the complex amplitudes A_n and A_{LO} are related, respectively, to the OFDM signal power P_n and the local laser power P_{LO} by

$$P_n = |A_n|^2/2 \tag{2.3}$$

$$P_{LO} = |A_{LO}|^2/2 \tag{2.4}$$

When the optical OFDM signal and the continuous wave (CW) light of the local laser are co-polarized by a polarization controller (PC), the optical fields incident on the upper and lower photodiodes after 180° optical hybrid can be given as

$$E_s(t) + E_{LO}(t) = E_1(t) + E_2(t) + \cdots + E_n(t) + E_{LO}(t) \tag{2.5}$$

at upper photodiode and

$$E_s(t) - E_{LO}(t) = E_1(t) + E_2(t) + \cdots + E_n(t) - E_{LO}(t) \tag{2.6}$$

at lower photodiode,

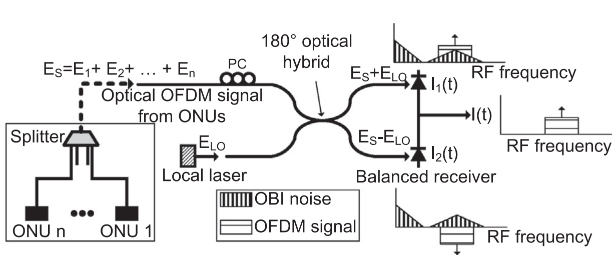

Fig. 1. OBI noise reduction in the OFDMA-PON link using self-homodyne balanced receiver.

where $E_s(t)$ is the total optical field from the first ONU to the nth ONU. The output photocurrent can be written as Eqs. (2.7) and (2.8),

$$\begin{aligned} I_1(t) &= R\left[\mathrm{Re}\left\{\frac{\sum_{k=1}^{n} A_k(t)\exp(j\omega_s t) + A_{LO}\exp(j\omega_{LO} t)}{\sqrt{2}}\right\}\right]^{ms} \\ &= \frac{R}{2}\left[\sum_{k=1}^{n} P_k(t) + P_{LO} + 2\sum_{k=1}^{n-1}\sum_{j=k+1}^{n} P_k(t)P_j(t)\cos(\theta_k(t) - \theta_j(t)) \right. \\ &\quad \left. + 2\sum_{k=1}^{n}\left[\sqrt{P_k(t)P_{LO}}\cos\{(\omega_s - \omega_{LO})t + \theta_k(t) - \theta_{LO}(t)\}\right]\right] \end{aligned} \tag{2.7}$$

$$\begin{aligned} I_1(t) &= R\left[\mathrm{Re}\left\{\frac{\sum_{k=1}^{n} A_k(t)\exp(j\omega_s t) - A_{LO}\exp(j\omega_{LO} t)}{\sqrt{2}}\right\}\right]^{ms} \\ &= \frac{R}{2}\left[\sum_{k=1}^{n} P_k(t) + P_{LO} + 2\sum_{k=1}^{n-1}\sum_{j=k+1}^{n} P_k(t)P_j(t)\cos(\theta_k(t) - \theta_j(t)) \right. \\ &\quad \left. - 2\sum_{k=1}^{n}\left[\sqrt{P_k(t)P_{LO}}\cos\{(\omega_s - \omega_{LO})t + \theta_k(t) - \theta_{LO}(t)\}\right]\right] \end{aligned} \tag{2.8}$$

where 'ms' indicates the mean square with respect to the optical frequency, 'Re' denotes the real part, and $\theta_k(t)$, $\theta_j(t)$ and $\theta_{LO}(t)$ are phases of the OFDM signal and local laser, respectively. R is the responsibility of the photodiode. As shown in Eqs. (2.7) and (2.8),

$$2\sum_{k=1}^{n-1}\sum_{j=k+1}^{n} P_k(t)P_j(t)\cos(\theta_k(t) - \theta_j(t)) \tag{2.9}$$

is the OBI noise, which is expressed in the product between multiple ONUs. Accordingly, the output of the balanced receiver can then be given as

$$\begin{aligned} I(t) &= I_1(t) - I_2(t) \\ &= 2R\sum_{k=1}^{n}\left[\sqrt{P_k(t)P_{LO}}\cos\{(\omega_s - \omega_{LO})t + \theta_k(t) - \theta_{LO}(t)\}\right] \end{aligned} \tag{2.10}$$

where P_{LO} is always constant and $\theta_{LO}(t)$ includes only the phase noise that varies in time. In the proposed scheme, Eq. (2.10) can be changed into Eq. (2.11) because self-homodyne detection ($\omega_s = \omega_{LO}$) is employed.

$$I(t) = I_1(t) - I_2(t) = 2R\sum_{k=1}^{n}\left[\sqrt{P_k(t)P_{LO}}\cos(\theta_k(t) - \theta_{LO}(t))\right] \tag{2.11}$$

As shown in Eq. (2.11), OBI noises, which are generated among multiple ONUs, are reduced perfectly, while the signal to noise ratio (SNR) of each OFDM signal can be improved significantly using balanced detection with the help of a local laser.

3. Experimental setup

Fig. 2 shows the experimental setup for the proposed scheme. The DMT signal with quadrature phase shift keying (QPSK) symbol mapping was generated by MATLAB® as an offline processing. The number of DMT subcarriers was 256 ranging from DC to 1 GHz. Some of DMT subcarriers (from the 20th subcarrier to the 120th subcarrier) were allocated for the first ONU, and the others (from the 135th subcarrier to the 240th subcarrier) were allocated for the second ONU. The fast Fourier transform (FFT) size was 512 due to Hermitian symmetry. The calculated DMT signal was loaded into a 2-Gs/s arbitrary waveform generator (AWG: Tektronix 7122B).

A continuous wave (CW) light was generated by an external cavity laser (ECL) with a center wavelength of 1550.19 nm. Its linewidth was 50 kHz when the output optical power was