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Performance improvement of a SOA-based coherent optical-OFDM transmission system via nonlinear companding transforms

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ABSTRACT

Coherent-Optical OFDM systems are known to be sensitive to large peak-to-average power ratio (PAPR) at the transmitter output, due to nonlinear properties of some components involved in the transmission link. In this paper, we investigate the impact of an amplification of such signals via a semiconductor optical amplifier (SOA), considering some recent experimental results. An efficient tradeoff between BER performance, computational complexity and power efficiency is performed by a proper design of Wang's nonlinear companding function, considered for the first time in an optical communication context. A BER advantage of around 3 dB can hence be obtained over a standard system implementation not using PAPR reduction. The designed function also proves to be more efficient than μ-law function, considered in the literature as an efficient companding scheme.

1. Introduction

Orthogonal frequency-division multiplexing (OFDM) is considered as a promising technology for future fiber-optic communication networks [1] because of its many advantages, such as high spectral efficiency, simple compensation of linear channel impairments (chromatic and polarization mode dispersions), dynamic bandwidth allocation capability in a multiuser context (OFDMA), and powerful digital signal processing (DSP)-based implementation via fast Fourier transform (FFT) operations. Also, various system implementation variants are permitted, namely intensity-modulated with direct detection (IM/DD), coherent optical OFDM (CO-OFDM) and all-optical OFDM (AO-OFDM), so that the technology can be adopted both for long-haul optical transmission links [2] and metropolitan/access networks [3,4]. However, a well known drawback of OFDM signals is their high peak-to-average power ratio (PAPR) [5], which can give rise to distortions due to nonlinear properties of digital-to-analog converters (DAC), optical modulator, transmission medium or power amplifier (PA). Optical amplifiers are key components for most fiber communications systems and networks [6,7], due to their ability to compensate losses of the optical signal without requiring its conversion to the electric domain. Some broadband wavelength conversion capabilities have also been reported through use of semiconductor optical amplifiers (SOA) [8], provided that the incoming signal has low PAPR. It has been recently pointed out by Khaleghi et al. [9,10] that SOA could be a pertinent choice for CO-OFDM signals' amplification for their large optical bandwidth, small size and possibility of integration at limited cost [11]. Through numerical simulations and experimental investigations, the feasibility of SOA-based CO-OFDM transmission is demonstrated by the authors and the influence of some system parameters such as input power, signal wavelength and number of subcarriers is examined in terms of error-vector-magnitude (EVM). It is well known that for power efficiency considerations, the PA should be operated close to its saturation region, which can translate into large EVM, intersymbol interference (ISI) and significant out-of-band radiation if a SOA is used, due to its fast gain dynamics and nonlinear intrinsic properties. In order to improve the performances of the system studied by Khaleghi et al., we propose here to investigate some predistortion techniques for the multicarrier waveform in the electrical domain, with a main focus on peak power reduction. PAPR reduction has been an intensive research area over the last decade (see [12,13] for recent surveys), due to the large number of subcarriers required for meeting high data rate and mobility demands. The many techniques identified in the literature can be broadly classified into signal distortion techniques, coding techniques and multiple signaling/probabilistic techniques. Most PAPR reduction methods have been investigated in a wireless communication context and relatively few references deal with

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the case of optical fiber communications. A short comparative study of a few methods, including Active Constellation Extension (ACE), precoding, selective mapping (SLM) and treillis shaping (TS), has been conducted by Goebel et al. [14]. More recently, a combination of SLM technique with optimized digital Mach–Zehnder (MZ) modulator pre-distortion has been proposed in [15]. Another approach is to use subcarrier pre-filtering [16] so as to reduce correlation between subcarriers. Hard clipping with predistortion was investigated in [17] and [18] to combat the nonlinearity in the MZ modulator, the nonlinear biasing and clipping effects being theoretically characterized in [19] for IM/DD optical OFDM systems. Biased clipping has also been proved to be beneficial for fiber nonlinearity mitigation in long-haul CO-OFDM systems [20]. Combining data clipping and random additional phases has also been investigated in [21] in the context of OFDMA-based passive optical access networks. Hence, hard clipping (HC) has attracted significant attention, mainly due to its simplicity. Nevertheless, it causes additional noise (both in-band and out-of-band) that can degrade system performances, especially for high data rate and high modulation orders. This clipping noise can be mitigated via filtering but at the expense of an extra complexity. Companding (soft clipping) techniques appear to be more suitable for most of the applications, for their ability to achieve excellent tradeoff between many factors that appear in the design of a PAPR algorithm: low computational complexity, no side information, good BER together with transparency to frame format, number of subcarriers, and constellation type. Such schemes rely on compressing large signals and enlarging small ones, in such a way that both PAPR reduction and immunity of small signals to noise are ensured. Until now, only μ-law companding has been considered in the field of optical communications [22–24]. Since its introduction in [25], many other Nonlinear Companding Transforms (NCTs) have been studied in the literature in order to avoid some drawbacks of μ-law scheme, namely increase in the average power and lack of flexibility. In the present paper, we demonstrate that the SOA-based CO-OFDM system of Khaleghi et al. can be significantly improved by the use of an efficient NCT design. By considering a general scheme recently proposed by Wang et al. [26], we can achieve a precise control of the probability function of the OFDM signal through the use of a limited number of parameters. This is the first time this kind of promising approach is investigated for optical communications. Thanks to global optimization of some key parameters of the NCT algorithm, it is shown that a 3 dB advantage over a standard system implementation can be achieved in the saturated regime. The good agreement of our results with the experimental data described in [10] proves the efficiency of the proposed setup and confirms that SOA could be a pertinent choice in a multicarrier optical transmission scenario.

2. CO-OFDM system model

In this study, we used a co-simulation setup of the CO-OFDM system which is similar to that used recently by Khalegi et al. [10], except that we implemented some blocks under Matlab rather than under VPItransmissionMaker for ease of companding algorithms implementation. The same SOA model is implemented using ADS software from Agilent Technology (the co-simulation involves ADS Ptolemy software); it relies on the carrier density rate and propagation equations of the optical signal field and the intensity of the Amplified Spontaneous Emission (ASE) noise. This model has been fitted to simulate a commercially available bulk 750 μm long SOA (INPHENIX-IPSAD1501), so that it yields a very good matching between simulated results and experimental results, as reported in [10]. The overall structure of the simulated system is illustrated in Fig. 1; it is very classical, except that we introduced a PAPR reduction block (the associated nonlinear companding will be explained in the next section).

The whole transmitter is implemented under Matlab, including laser diode (implemented according to [27]) and I/Q optical modulator (use of a standard nonlinear model as described in [28]). Our aim being to demonstrate the benefits of some PAPR reduction algorithms only, in the presence of optical amplifier, we will assume in the following a linear electrical channel at IQ modulator input, a perfect coherent optical detector (ideal photodetectors), together with a perfect compensation of the laser phase noise on the receiver side; also influence of propagation

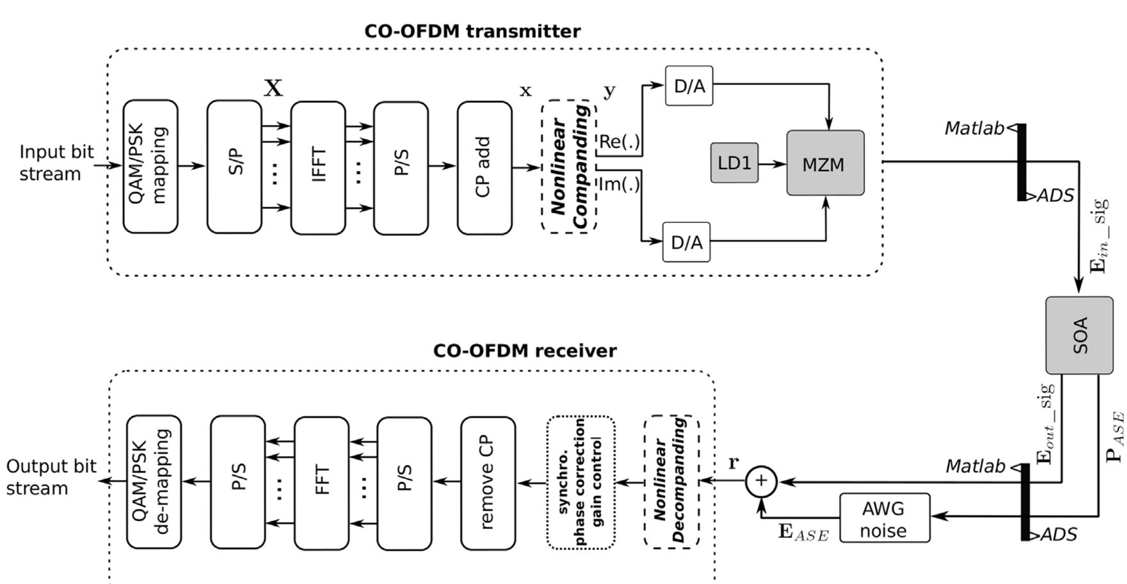

Fig. 1. Block diagram of the CO-OFDM system with Matlab/ADS co-simulation, including nonlinear companding (S/P: serial to parallel; IFFT: inverse Fast Fourier Transform; CP: Cyclic Prefix; D/A: Digital to Analog conversion; AWG: Additive White Gaussian).