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PAPR reduction based on chaos combined with SLM technique in optical OFDM IM/DD system

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This paper proposes a method to decrease the PAPR of 16-quadrature-amplitude-modulation (16QAM) orthogonal-frequency-division-multiplexing (OFDM) signal. The method is to combine chaos with selected mapping (CSLM) technique so that the chaotic sequences are able to control generation of phase rotation factors. The research has utilized this method to transmit OFDM signal along 100 km long single-mode fiber in an IM/DD system to test OFDM signal performance. Our experimental results show that the receiver sensitivity is improved by about 1.4 dB when a 3.28 GB/s OFDM signal at a bit error rate of 1×10^{-3} is launched by transmission power at 2, 6, 8 and 10 dBm, respectively. Moreover, comparison with traditional SLM technique, the CSLM technique can improve the BER of the system.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) technique has recently become a hot research spot in optical communications mainly due to three merits: first of all, it is its high spectral efficiency; Secondly, it can effectively reduce both inter-symbol interference (ISI) caused by a dispersive channel and intercarrier interference (ICI) from the received signal, which has already been utilized in broadband cable and wireless communication systems [1–4]; Thirdly, it is immune to chromatic dispersion (CD) and polarization mode dispersion (PMD) [5–12]. However, high peak-to-average power ratio (PAPR) has been a major drawback of OFDM signal so that many components in a system must be ideally linear in a wide dynamic range to avoid nonlinear distortion [13,14]. Especially in a wavelength-division-multiplexing (WDM) system, the OFDM signal over an optical fiber channel is summation of those of individual sub-channels, hence high performance of Erbium-doped optical fiber amplifier (EDFA) has to be considered to overcome nonlinear distortion, plus EDFA works in prolong high power consumption mode, these two factors cause the hardware cost as well as production cost increases. In addition to those disadvantages, as the probability of the real-time power exceeding maximum power greatly increases, the probability of EDFA will exceed linear range and cause serious nonlinear effects increases accordingly. We have tried different approaches to reduce the PAPR including: utilizing phase modulation instead of intensity modulation [15], adopting a compression transform coding technique [16] and combining Hadamard transform with compression transform coding technique [17]. There are also other methods [18–20] such as amplitude-clipping, selected mapping (SLM) and partial transmit sequence (PTS) have been explored by other researchers. When there is no linear distortion, by using aforementioned approaches, SLM method can statistically improve the characteristics of the PAPR distribution of the OFDM signal as many OFDM transmission systems with SLM for PAPR reduction have been demonstrated [20,21]. However, among these SLM techniques, a huge amount of overhead information has to be transmitted in order to properly demodulate data. As a result, data transmission efficiency is unavoidably reduced. Moreover, prior to using inverse fast Fourier transform (IFFT), independent phase rotation factors of SLM scheme are randomly generated, therefore the opportunities of selecting OFDM signal with minimum PAPR is very few. Although there are articles using SLM without requiring overhead information [22–25], a small amount of redundant information has to be introduced at the transmitter or the decoding algorithm is complicate in the receiver for data recovery.

Chaotic system has good pseudo-random characteristics, such as extremely sensitive to initial conditions, non-periodic, noise-like, deterministic and reproducible, which has been used in secure communication system [26–28]. In fact, consolidating chaotic system into OFDM can not only secure data, but also provide more opportunities of selecting OFDM signal with the smallest PAPR. The reason is the amount of independent phase rotation factors with good performance greatly increases in a CSLM system. One of potential applications to use the CSLM technique to generate

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phase rotation factors for SLM method in order to reduce PARA of OFDM signal. Furthermore, in the CSLM system, only overhead information to be transmitted is initialization conditions, which greatly improves data transmission speed. Ref. [29] has proposed an improved SLM method based on chaotic phase sequences, but it has only discussed the CCDF curve without applying into optical OFDM transmission system.

In this paper, we experimentally demonstrate how to reduce PAPR of an optical OFDM signal via an intensity-modulation/direct-detection (IM/DD) system based on CSLM technique. As mentioned earlier, the first step is to generate phase rotation factors using CSLM technique to capture a 3.28 Gb/s OFDM signal with minimum PAPR, and then transfer this signal along 100 km long standard single-mode fiber (SSMF). There will be three outstanding outcomes to be summed up when comparing with traditional SLM method: (1). both sensitivity and BER performance of the receiver greatly improves due to PAPR reduction; (2). data transmission efficiency greatly increases due to less overhead information; (3). the system is simplified so that it is easy to implement as the redundant information will not increase in terms of phase sequence.

The rest of this paper is organized as follows. In Section 2, we propose the CSLM technique based on Logistic map and Chebyshev map for PAPR reduction. In Section 3, we list the experimental results of optical OFDM IM/DD system based on CSLM technique for PAPR reduction. The last section is the conclusion.

2. Principle of the CSLM technique

2.1. CSLM technique

At present, one-dimensional discrete chaotic systems are based on Logistic map, modified Logistic map, Chebyshev map and Tent map [30,31]. In order to generate chaotic signals with more complicated dynamic behaviors, cascade discrete chaotic system concept has been presented [32]. However the bifurcation parameter of the system is fixed to a constant, the security of the system needs to be improved. In this paper, based on Logistic map and Chebyshev map, a novel hybrid chaotic system is defined as follows:

$$\begin{cases} y_{k+1} = 1 - \mu(x_k, y_k) \cdot x_k^2 \\ x_{k+1} = \cos(\omega(x_k, y_k) \cdot \cos^{-1}(y_k)) \end{cases} \quad (1)$$

where the parameters $\mu(x_k, y_k)$ and $\omega(x_k, y_k)$ are functions of x_k and y_k. These two parameters are time-base parameters calculated from x_k and y_k, not like an independent chaotic mapping system where constants are usually used. To simplify calculation, $\mu(x_k, y_k)$ and $\omega(x_k, y_k)$ can be expressed as:

$$\mu(x_k, y_k) = \begin{cases} |x_k| + 1, & |x_k| < 0.5 \\ 2, & |x_k| \geqslant 0.5 \end{cases} \quad (2)$$

$$\omega(x_k, y_k) = \mathrm{mod}(Int(\lambda y_k), 6) + 2 \quad (3)$$

where $\mu(x_k, y_k)$ is a piecewise linear function, while λ is a coefficient to $\omega(x_k, y_k)$. As the system is very sensitive to initial conditions, when bifurcation parameters randomly vary in a defined range, the hybrid chaotic system produces very complex chaotic signals. Furthermore, the stochastic performance of the system is greatly enhanced, so does the system's unpredictability. Therefore when the configurations of two chaotic systems are identical at both transmission and receiver ends with a small initial difference, chaotic sequences will diverge very quickly in a short period of time and is independent of each other.

Fig. 1 illustrates two different correlation characteristics of signal x_k of its output length equivalent to 1024 sequences when all conditions are the same with exception of different random initial values. From Fig. 1(a), we can see the self-correlation is an approximate pulse function, while the mutual correlation is about zero. From Fig. 1(b), the mutual correlation of chaotic sequences is near zero. When chaotic sequences are infinite long, mutual correlation value is considered to be zero. As we can see that the generated chaotic sequences have good correlation characteristics properties.

2.2. OFDM modulation with CSLM technique

In Fig. 2, at the transmission end, when initial condition $(x_0, y_0)^n$, $1 \le n \le K$ is defined, the CSLM system generates real-time chaotic sequences after N times iteration of Eq. (1). Since the real-time chaotic sequences cannot be directly acted as phase rotation factors $p^n = [a_0^{(n)}, a_1^{(n)}, \ldots, a_{N-1}^{(n)}]$ (in which $a_i^{(n)} = R_{a_i^{(n)}} + jI_{a_i^{(n)}}$), we use digital signal processing (A/D converter) to convert the chaotic real-time analog sequence into digital. For the sake of simplicity, $a_i^{(n)}$ is determined by the following equation:

$$\begin{cases} R_{a_i^{(n)}} = \mathrm{sign}(\mathrm{mod}(Int(\eta x_k), 256) - 128) \\ I_{a_i^{(n)}} = \mathrm{sign}(\mathrm{mod}(Int(\eta y_k), 256) - 128)) \end{cases} \quad (4)$$

Base on this equation, the generated phase rotation factors will look like: $p^n = [a_0^{(n)}, a_1^{(n)}, \ldots, a_{N-1}^{(n)}]$, $a_k^{(n)} \in \{\pm 1 \pm j\}$. As long as discrete sequences are being processed by constellation mapping, the sequence data becomes a matrix of $X = [X_0, X_1, \ldots, X_{N-1}]^T$, where X_k represents corresponding subcarrier data. In the CSLM transmitter, the input sequence X is expanded to K times of identical sequences. Each of sequence does dot product with different phase rotation factors p^n. Therefore,

$$\begin{aligned} C^{(n)} &= X \cdot * p^{(n)} \\ &= [X_0 a_0^{(n)}, X_1 a_1^{(n)}, \ldots, X_{N-1} a_{N-1}^{(n)}]^T \end{aligned} \quad (5)$$

where $\cdot *$ denotes the dot product of two vectors. After processing the IFFT calculation of each sequence, the OFDM signal can be expressed as:

$$\begin{aligned} x_m^{(n)} &= \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} C^{(n)} \exp(j2\pi km/N) \\ &= \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k a_k^{(n)} \exp(j2\pi km/N) \end{aligned} \quad (6)$$

The PAPR of $x_m^{(n)}$ is defined as:

$$PAPR^{(n)} = \frac{\max_{0 \leqslant m \leqslant N-1} |x_m^{(n)}|^2}{E[|x_m^{(n)}|^2]} \quad (7)$$

In order to analyze the PAPR statistic characteristics of the OFDM system, the complementary cumulative distribution function (CCDF) of PAPR is a parameter to be commonly discuss, and it can be expressed as

$$\Pr(PAPR > z) = 1 - (1 - e^{-z})^N \quad (8)$$

where N is the number of branches.

In Fig. 3, it illustrates different CCDF curves of the original OFDM signal when not using SLM technique, or using CSLM technique with different number of branches where K (=2, 4, 8, 16, 32) (Please note that the red curve is without using SLM technique). As we can see that the CCDF performance of OFDM signals are getting better and probability of peak power greater than a set point are getting lower as K increases, which is coincident with Ref. [33], though the transmission speed is getting slower. In consideration of system cost, it would be appropriate to use $K = 16$ in a CSLM system where the PAPR of OFDM signal is 3.5 dB lower when the CCDF is at 10^{-4} comparison to a system without using SLM technique.