Paper

Chaotic-based Orthogonal Frequency Division Multiplexing with Index Modulation

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https://doi.org/10.26636/jtit.2022.165422

Abstract — Orthogonal frequency division multiplexing with index modulation (OFDM-IM), stands out among conventional communication technologies, as it uses the indices of the available transmit entities. Thanks to such an approach, it offers a novel method for the transmission of extra data bits. Recent years have seen a great interest in chaos-based communications. The spectrum-spreading signals used in chaotic signal modulation technologies are orthogonal to the existing mixed signals. This paper presents how well a non-coherent differential chaos shift keying communication system performs across an AWGN. Different types of detection methods are simulated, bit error rate and power spectral density are calculated and then compared with standard OFDM with index modulation. The results of simulations concerning the performance of a DCSK system, adding to the security of the proposed solution and offering a comparable bit error rate performance, are presented in the paper as well.

Keywords — AWGN, chaos communications, DCSK, index modulation.

1. Introduction

In the literature, a wideband chaotic signal is used in chaotic communication channel as the carrier [1] in order to ensure an efficient form of communication compared with channels relying on multipath fading. As a result, the popularity of chaotic communication networks is similar to that of ultra-wideband communication systems [6]–[4] and spectrum communications [5]. The keying technique in differential chaos (DCSK) offers great performance while using a straightforward auto-correlation receiver (ACR) on time-varying or multipath fading channels, as shown in [7]. DCSK has been also thoroughly studied in a variety of communication scenarios, including wireless personal area networks (WPANs) in paper [8] and MIMO systems in articles [9], [10].

The development and analysis of an orthogonal multilevel code-shifted differential chaos shift keying built on OFDM (OFDM-OMCS-DCSK) proved that a chaotic signal that is capable of achieving high data rates with the use of the same time slot is created using the hybrid Gram-Schmidt algorithm and the Walsh coding function, thus providing a higher bandwidth efficiency compared with conventional solutions. Furthermore, BER performance of AWGN and multipath Rayleigh fading channels shows that the OFDM-OMCM-DCSK system achieves the best BER result, with a high data rate characteristic compared with OFDM-DCSK [11].

Paper [12] proposes a permutation index modulation model and a position index modulation OFDM-based chaotic multi-carrier communication system. It combines position and permutation index modulation, adding a new dimension for data transmission and enhancing spectrum efficiency. Thanks to multi-carrier modulation, the system also offers improved multipath immunity. The system's BER performance is compared with that of PI-DCSK, CCPK-OFDM, and CCPK. The outcomes of the simulations prove that it is an effective, non-coherent modulation technique [12].

In [13], the chaotic sequence was generated by modifying a tent map, one of the well-known chaos generators, to boost security. Performance tests and security analyses were conducted using the BER, mean squared error (MSE), and correlation metrics. The outcomes showed that the autocorrelation of the suggested tent map acts as a delta function, making it challenging to separate the signal's content from the noise. It also showed how much more sensitive the suggested tent map was to variations in the initial state and control parameters. Using the proposed method, the multi-carrier CSK system outperforms the CSK in terms of data transmission rate.

Paper [14] presents SR-ODBR-DCSK – a modulation system with an orthogonal double bitrate based on the DCSK technique. To transmit two signals simultaneously, the Walsh function is used and the continuous two-bit data information is modulated utilizing orthogonality of the chaotic signals, with the modulation technology generating two orthogonal chaotic signals. This method is compared with SR- DCSK and the results show good effectiveness of the SR-ODBR-DCSK system [14].

Although many systems with a chaotic map have been proposed in the literature to ensure secure transmissions using synchronization, these systems do not consider the use an OFDM-enhanced index-modulation system-based chaotic map. Therefore, the main objective of this paper is to design a chaotic-based OFDM-IM system that ensures a significant improvement in the performance in the noise channel and enhances the performance of the fading channel, as well as ensures a secure transmission via chaotic signals and achieves better spectral efficiency. The proposed technique, transmitting data based on the indices of the active subcarriers of orthogonal frequency division multiplexing (OFDM), is known as index modulation-aided OFDM (OFDM-IM) and allows to create a multicarrier transmission technique with a high spectral and energy efficiency in 5G networks.

Index modulation (IM) is a new concept. It is a modulation technique that uses the index of several mediums to modulate the carrier, with the incoming data bit to be transmitted being divided into two parts. One part is used to modulate the phase and amplitude of the carrier and the other part is used to select the index (I) of the activated antenna that transmits the matching modulated signal. OFDM-IM may be employed in frequency, permutation, coding [15], and time domains [16].

The remainder of this article is organized as follows. Section 2 describes the proposed OFDM-IM based chaotic communication scheme. Section 3 covers the simulation results and presents a discussion, while Section 4 evaluates the performance. Finally, Section 5 presents the conclusion.

2. OFDM-IM with DCSK

Due to their sensitivity to initial values of signals produced by deterministic nonlinear dynamical systems [17], also such advantages of spread spectrum signals' as the reduction of multipath fading, anti-jamming, suppression of inter-user interference and secure communication, are used to define chaotic signals here. Coherent and non-coherent detection are the two basic categories in chaotic communication systems. A precise reproduction of the chaotic carrier that was used to modulate the information must be made at the receiver in coherent systems. Since chaotic synchronization at the receiver and accurate replication of the chaotic signals are not necessary for coherent systems, more chaotic digital modulation techniques have been proposed in recent years.

In DCSK, two chaotic sample functions represent each bit of information that will be transferred. While the first sample function acts as a reference, the second sample function conveys the data. By delivering a reference signal produced by a chaos generator in a row, bit 1 is transmitted, whereas bit -1 is sent by using a reference chaotic signal followed by an inverted copy of the same signal [18]. DCSK seems to be less sensitive to channel distortion, as distortion affects both the reference and data samples [19].

2.1. Chaotic Generator

Chaotic systems can be divided into two categories: those defined by flows or differential equations and those characterized by chaotic maps. The definition of a chaotic concept is formulated as:

$$c(t) = \begin{cases} x(t), & \text{for } (l-1)T \leqslant t < \left(1 - \frac{1}{2}\right) T \\ x\left(t - \frac{T}{2}\right), & \text{for } \left(l - \frac{1}{2}\right) T \leqslant t < lT \end{cases}. \quad (1)$$

If the l symbol is $+1$, Eq. (1) takes the form of:

$$c(t) = \begin{cases} x, & \text{for } (l-1)T \leqslant t < \left(1 - \frac{1}{2}\right) T \\ -x\left(t - \frac{T}{2}\right), & \text{for } \left(l - \frac{1}{2}\right) T \leqslant t < lT \end{cases}. \quad (2)$$

When the symbol is -1, T and $c(t)$ stand for the bit duration and chaotic reference signal, respectively.

In this paper, three different kinds of chaotic maps are employed, namely those of the Lorenz, Henon, and quadratic type. The Lorenz three-dimensional chaotic map is generated using [20]:

$$\begin{aligned} X_{n+1} &= 1 = X_n Y_n - Z_n + bY_n \\ Y_{n+1} &= X_n \\ Z_{n+1} &= Y_n \end{aligned}, \quad (3)$$

where: $-1 < X < 1$, $-1.5 < Y < 1.5$, and $-1.5 < Z < 1.5$.

The Henon map system is generated as [21]:

$$\begin{aligned} X_{n+1} &= 1 = aX_n^2 + bY_n \\ X_{n+1} &= X_n, \end{aligned} \quad (4)$$

where $a = 1.4$ and $b = 0.3$ are system parameters.

The quadratic chaotic map is not linear but still is deterministic because the behavior of the system is defined by an equation which determines how the behavior of the map varies when the initial value of X_0 changes [22]:

$$X_{n+1} = a - X_n^2, \quad (5)$$

where n is an iteration number and α is a chaotic parameter. For $\alpha = [1.5, 2]$, the system is considered as chaotic.

Without adverse effects for generalization, we assume that the subcarrier is used to send the reference chaotic signal. It is defined as:

$$c = \{x(1), x(2), \ldots, x(\beta)\}, \quad (6)$$

where $x(\beta)$ is generated by a chaotic map and β is the spreading factor in DCSK.

The transmitter structure of an OFDM-IM-based chaotic system using N subcarriers is shown in Fig. 1, while Tab. 1 presents the parameters of the system.

2.2. Transmitter Architecture

Using the OFDM scheme and applying index modulation with DSCK to its signal, a total of m data bits are split into G subblocks within $n = N/G$ subcarriers, where $N = 2, 4, 8\ldots$ and $1 < k < N$. The subcarrier indices can carry P_1 bits of index data as:

$$p_1 = \lfloor \log_2 C(n,k) \rfloor, \quad (7)$$

where $C(\cdot,\cdot)$ denotes the binomial coefficient. Each $p = m/G$ bit subblock is then used for index modulation. Due to the same and independent features of all activities within the subblocks, we can use the example of the β-th subblock, where $\beta \in \{1, \ldots, G\}$ separates the incoming p bits into two parts. The first component made up of p_1 index bits

Tab. 1. OFDM-IM parameters and symbols used.

Parameters	Description
M	Number of information bits in each OFDM block
p_1	The total number of bits that each subblock's active indices are mapped to
p_2	Each subblock's total amount of modulation bits expressed as $p_2 = k \log_2 m$
m	m-ary modulation size
G	Number of groups, with p bits in each group
p	The number of bits per group ($p = m/G$)
N	OFDM subcarriers count
K	Each subblock's active subcarrier count
$I(\beta)$	Chosen indices for the subblock
$s(\beta)$	Modulated subblock symbol
$c(t)$	Chaotic map

determines the subcarrier activation pattern (SAP) for the β-th subblock or the indices of the k active subcarriers.

$$\mathbf{M} = \begin{bmatrix} b_{1,1} & b_{1,2} & \cdots & b_{1,N} \\ b_{2,1} & b_{2,2} & \cdots & b_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ b_{G,1} & b_{G,2} & \cdots & b_{G,N} \end{bmatrix}. \tag{8}$$

Assuming the subcarriers are ordered in an ascending order, the following information can be obtained:

$$I^{(\beta)} = \left\{ i_1^{(\beta)}, \ldots, i_k^{(\beta)} \right\}. \tag{9}$$

In the proposed system:

$$\mathbf{I} = \begin{bmatrix} I_{1,1} & I_{1,K} \\ I_{2,1} & I_{2,K} \\ \vdots & \vdots \\ I_{G,1} & I_{G,K} \end{bmatrix}, \tag{10}$$

where $K = 1, \ldots, k$.

The data symbol vector is produced by the second part which consists of $p_2 = k \log_2 M$ symbol bits:

$$S^{(\beta)} = \left[s_1^{(\beta)}, \ldots, s_k^{(\beta)} \right]^{\mathrm{T}},$$

$$\mathbf{S} = \begin{bmatrix} S_{1,1} & S_{1,p_2} \\ S_{2,1} & S_{2,p_2} \\ \vdots & \vdots \\ S_{G,1} & S_{G,p_2} \end{bmatrix}, \tag{11}$$

where $S_k(\beta) \in \mathbf{S}$ with $K = 1, \ldots, k$ and $\mathbf{S}$ is the modulation of DCSK. Since there are $C(n, k)$ possible realizations of $\mathbf{I}(\beta)$, the mapping from p_1 bits to $\mathbf{I}(\beta)$ can be realized by a lookup table or the combinatorial method in OFDM-IM with PSK modulation, where each bit maps to one-bit complex number. In the proposed system each bit in the message is represented by 10 bits, which is a processing gain. Consequently, the transmitted signal, $e(t)$ is:

$$e(t) = \begin{cases} x_{i,k}, & \text{for } 1 < k \leqslant \beta \\ s_i x_{i,k-\beta}, & \text{for } 1 - k \leqslant 2\beta \end{cases}. \tag{12}$$

A graphical representation of Eq. (12) is presented in Fig. 1.

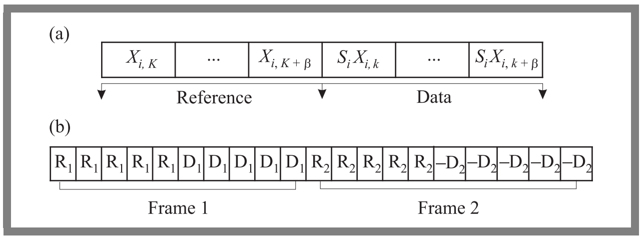

Fig. 1. Graphical representation of transmitted signal: a) general form and b) example for $m = 1, -1$.

Then on input the inverse FFT (IFFT) block of the same processes as those of classical OFDM are used:

$$X_T = \frac{N}{\sqrt{k}} \text{IFFT}\{X_F\} = \frac{1}{\sqrt{k}} W_N^H X^F, \tag{13}$$

where X_F is the cyclic prefix (CP) of length $[X(N-L+1) \ldots X(N-1)X(N)]^{\mathrm{T}}$, WN: is the discrete Fourier transform (DFT) matrix with $w_N^H W_N$, $\frac{N}{\sqrt{k}}$ is the normalization term, and L is the cycle prefix length.

Next, parallel-to-serial (P/S) and digital-to-analog (D/A) conversions are performed. Finally, an AWGN channel is used to transmit the generated signals (Fig. 2).

2.3. Receiver Architecture

At the receiver end, after removing CP from the received signal and performing N-point FFT [23], the analog domain input-output relationship in the frequency domain is established by:

$$y = Hx + n, \tag{14}$$

in the formula entries of the channel matrix $\mathbf{H} = \text{diag}\{h(1), \ldots, h(N)\}$ are complex Gaussian random variables with zero mean and unit variance, i.e. $h(\alpha?) \sim \text{CN}(0, 1)$, and n denotes the additive white Gaussian noise (AWGN) vector with $n(\alpha) \sim \text{CN}(0, N_0)$. It is assumed that each non-zero symbol has an average transmit power of ϕEs, where $\phi = N/K$ is the power allocation coefficient and Es is the average power per sub-carrier. Thus, the average signal-to-noise ratio (SNR) per active sub-carrier is given by $\gamma = \phi Es/N_0$.

Next, the output detector is compared with zero thresholds to recover the i-th information bit. There are three main types of detection algorithms used in the OFDM-IM system that map the incoming information bits to the subcarrier indices [24]:

– maximum likelihood (ML),

– log-likelihood ratio (LLR),

– greedy detector.

This method employs the ML detector, since the receiver has to know the set of possible indices for ML decoding. The ML detector for the OFDM-IM scheme considers all

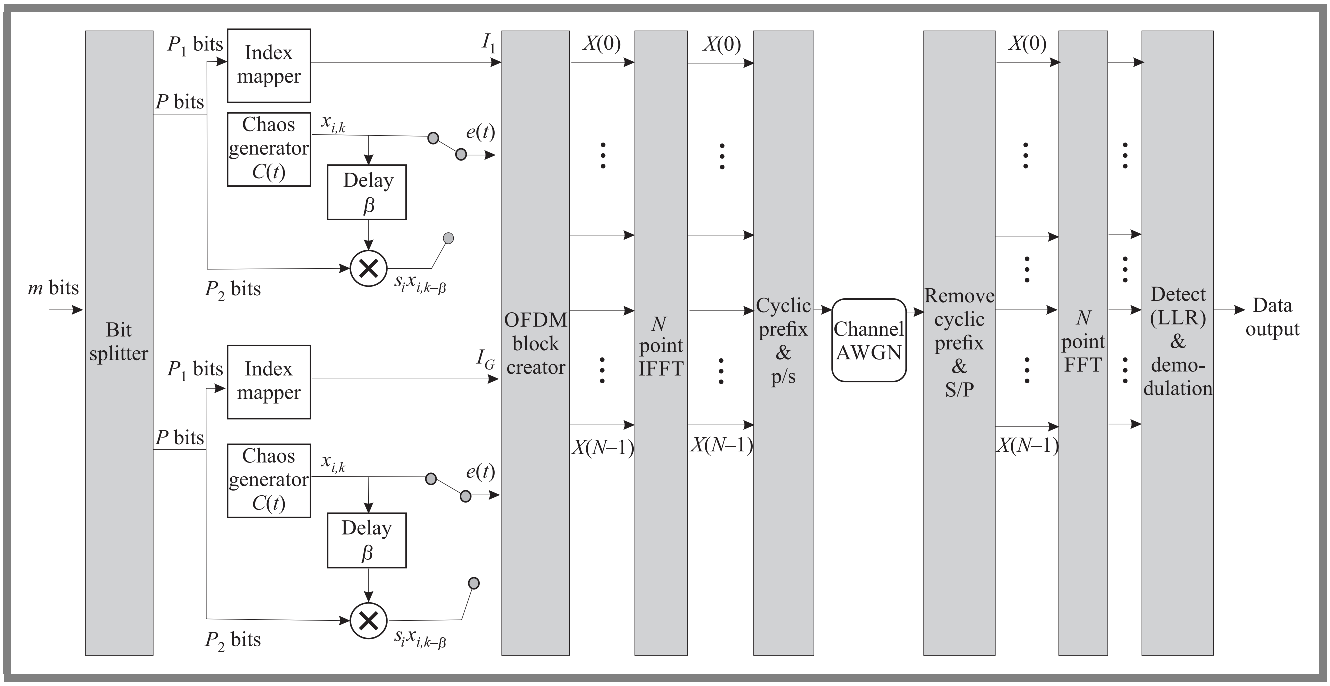

Fig. 2. OFDM-IM-based chaotic block diagram.

possible subblock realizations by searching for all possible subcarrier index combinations and signal constellation points, but the search complexity of the ML detector is of the order of $\sim O(\mathrm{CM}^k)$ per subblock, which becomes impractical for large C and k values.

Therefore, the receiver uses the log-likelihood ratio (LLR) detector to identify the most likely active subcarriers and the associated constellation symbols. LLR is an easy-to-use method based on combinatorial number systems. The BER simulation shown in Fig. 3 illustrates low dependability of the SAP detection method. We achieve BER about 10^{-3} in the greedy detector and about 10^{-4} with ML and LLR. Nevertheless, the greedy detector of OFDM-IM performs much worse than any other detectors due to the low reliability of the SAP detection approach.

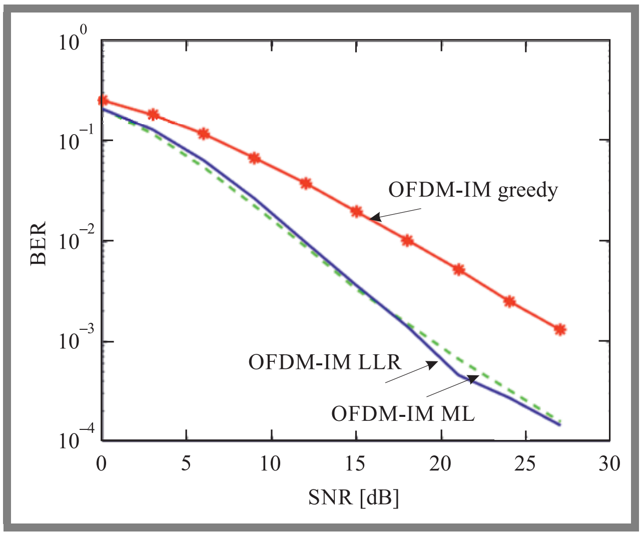

Fig. 3. Comparison of BER performance for different OFDM-IM detection types.

3. Results and Discussion

In the proposed system, a Lorenz-type 3D map is used, as shown in Fig. 4, where the first subplot displays a chaotic map $\in \{-1, 1\}$ with a size equal to 10,000 with a spreading factor of 10. The second subplot is the message bit sequence with 100 random bits, while the third subplot is the modulated data with the same range as the chaotic map and is generated by a check bit sequence if it equals 1 or -1, and by copying five symbols of the chaotic map and duplicating them or inverse and send it to throw a channel. In Fig. 5, the same procedure is used but with a different initial state.

The simulation parameters of the system are summarized in Tab. 2.

4. Performance Evaluation

The simulation results are presented in terms of BER probability and the Eb/No ratio, expressed in decibels, where Eb is the energy per user bit, and No is the single-sided spectral noise density. Here, we assume that channel interference is solely of the AWGN variety.

The goal of each communication system is to reduce BER. Channel disruptions, including noise and fading, are the main sources of errors. By limiting the effects of channel disruptions on the sent signal, the bit error rate can be decreased and, thus, the system optimized. Figure 6 shows BER for several chaotic map types, while Fig. 7 gives a comparison between OFDM

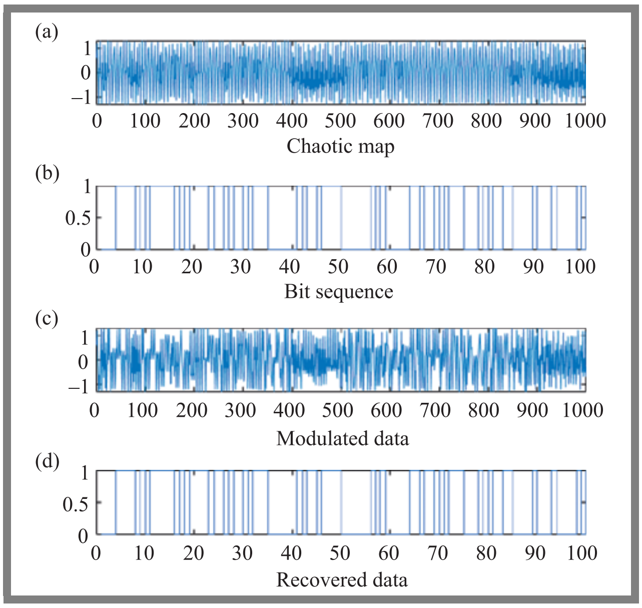

Fig. 4. a) Chaotic map generator, b) bit sequence, c) data modulated using DCSK, d) recovered data with the same initial value.

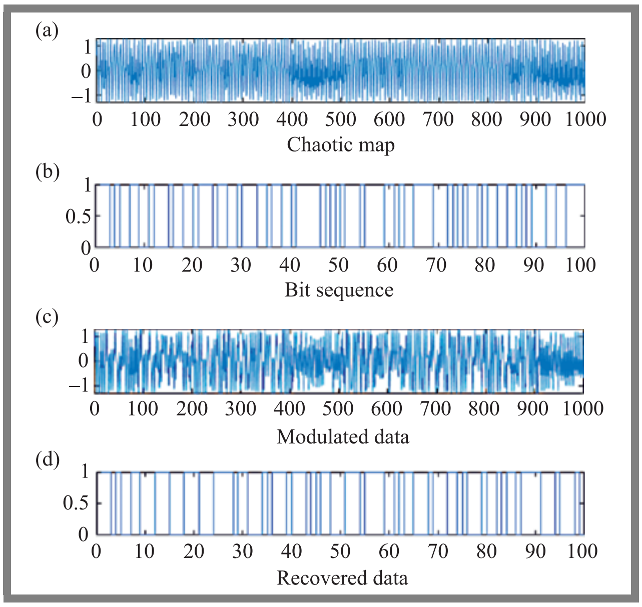

Fig. 5. a) chaotic map generator, b) bit sequence, c) data modulated using DCSK, d) demodulated data with a different initial state.

with index modulation and the proposed OFDM-IM-based chaotic system.

Figure 8 presents BER for an OFDM-IM-based chaotic system, for various channel state information.

Figure 9 shows a Lorenz map based on the proposed system and OFDM-IM transmitted symbols before transmission over the AWGN channel. With the Hamming window and 1024 FFT, the bandwidth of the system is 20 MHz and the PSD used of the two systems is near equal when $x = 0$, $y = -44.78$ in the chaotic system but in PSK, when $x = 0$, $y = -42.72$.

Figure 10 shows the PSD of the proposed system based on a Lorenz map and OFDM-IM transmitted symbols after transmission over the AWGN channel. The PSD of the two systems varies by approx. 20 dB, due to the effect of the

Tab. 2. Simulation parameters.

Parameter values	Chaotic with OFDM-IM	OFDM-IM
N	4	4
Modulation type	DCSK	PSK
Alphabet size, M	2	2
K	2	2
Number of sample per frame	10000	10000
Length of chaotic map	1000	/
F_s	20 MHz	20 MHz
CP (cyclic prefix)	1	1
FFT	64	64
Window	Hamming	Hamming

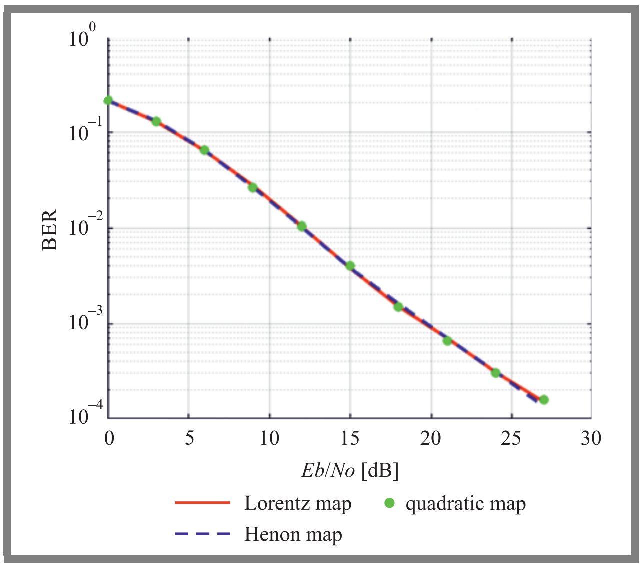

Fig. 6. Comparison between different types of chaotic maps.

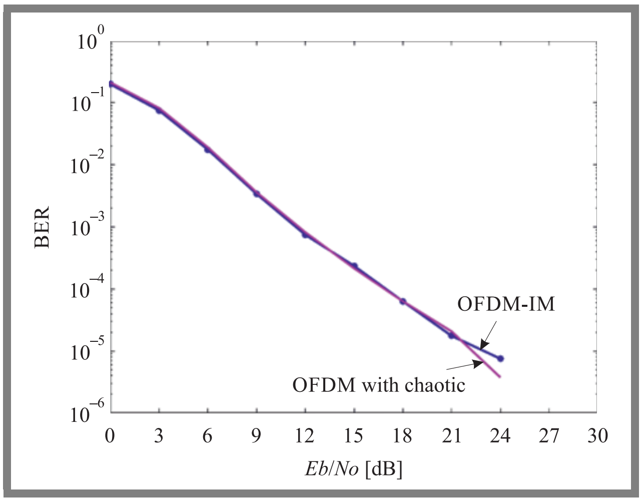

Fig. 7. BER Comparison between OFDM-IM and OFDM-based chaotic system.

channel on the system which transmitted the signal after the channel and the effect of AWGN when $x = 0$, $y = -62.73$ in BPSK. In the chaotic system, when $x = 0$, $y = -63.46$.

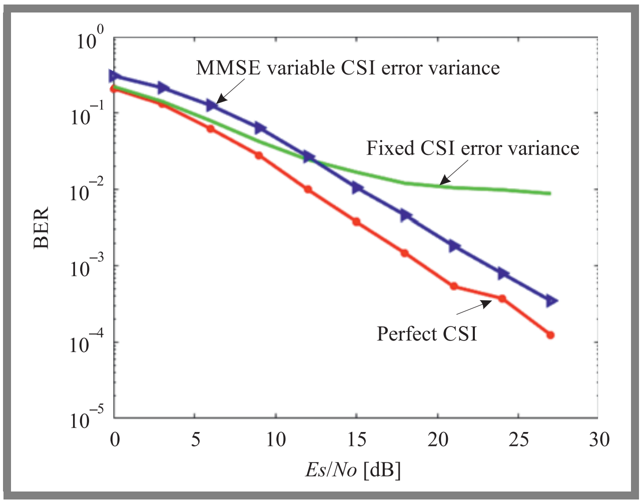

Fig. 8. OFDM-IM BER comparison for various channel states.

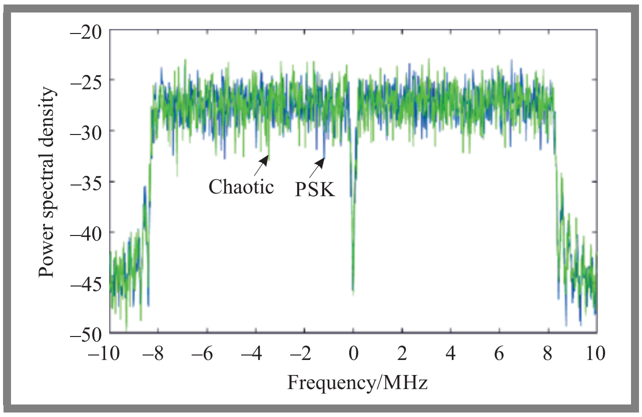

Fig. 9. OFDM-IM and a chaotic system before AWGN.

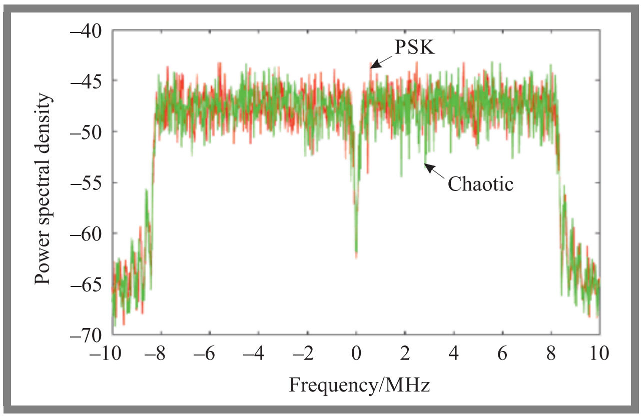

Fig. 10. Power spectral efficiency of OFDM-IM with chaotic after adding AWGN.

5. Conclusion

This paper presents a new combination of DCSK modulation with an OFDM-IM system. The goal behind using OFDM with index modulation and the DCSK system is to incorporate the benefits of both modulations, including robustness to impulse noise, high data throughput, and simplified equalization in multipath propagation. A comparison between different types of detection algorithms for OFDM-IM-based chaotic communication is presented and compared with the performance of BPSK and DCSK. The simulation results for a practical AWGN channel show that the simulated results are not worse in terms of PSD and BER than those of other traditional systems where the signal is recovered error-free at 27 dB. The proposed system provides a higher security level compared with traditional systems.

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