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SECURE INDEX WITH OFDM-IM-BASED CHAOTIC SYSTEM

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***Abstract*- Orthogonal Frequency Division Multiplexing-Index Modulation (OFDM-IM) based on chaos is a communication technique that uses chaotic systems to enhance the security of OFDM-IM systems. In this technique, chaotic signals are used to modulate the index values of the subcarriers and the data using DCSK, resulting in a more robust and efficient transmission. OFDM-IM uses the activated index as an information-carrying unit, which increases data rate and spectral efficiency. In this paper, we propose a secure index strategy for our system using a logistic map and Henon map to generate the chaotic signals, considering additive white Gaussian noise (AWGN) and the Raleigh fading channel. A lookup table based on the chaotic system was created using the indices of a randomized index modulation scheme with DCSK modulation. Even if the active subcarriers and their symbols are correctly calculated until the opening frame, the randomized index modulation prevents eavesdroppers from accurately determining message bits.**

keywords: Orthogonal Frequency Division Multiplexing, Secure Index, Chaotic System, DCSK, Index Modulation

I. INTRODUCTION

Secure Index Modulation (SIM) is a technique used in wireless communication systems to achieve secure and reliable information transmission. It combines traditional index modulation (IM) with physical layer security (PLS) techniques to enhance the security of wireless communication systems. Index modulation (IM) is a practical digital modulation method for next-generation wireless networks because of its benefits, including great bit error rate performance and better energy economy [1] [2]. Orthogonal frequency division multiplexing (OFDM-IM) is one of the most effective implementations of IM [3] [4], using the indices of subcarriers to transmit additional information. Subcarrier index modulation (SIM-OFDM) was the name given to the first effort at this concept [5]. However, there was a difficulty with error propagation brought on by incorrectly detecting a subcarrier state, which was fixed by an improved SIM-OFDM technique [6].

The authors of [7] established that the error performance of IM bits is better than that of conventional data symbol modulation (DSM) bits, and they also came up with the name OFDM-IM. The use of various signal constellations for IM has received some attention to increase BER performance and spectral efficiency (SE) [8–11]. The first system proposed in [12] was the dual-mode OFDM system. (DM-OFDM). Each of each subcarrier's two components is modulated by one of two different signal constellations. In [13], the authors proposed a novel technique called multiple-mode OFDM-IM that modulates n subcarriers using n different signal constellations as well as n permutations of those constellations (MM-OFDM-IM). The IM bits were transmitted using signal constellations of varied sizes, and they were enhanced to generalize MM-OFDM-IM [14]. MM-OFDM-IM can transfer more information bits than traditional OFDM-IM and DM-OFDM due to the permutation method used to modulate subcarrier indices instead of the combinatorial method [15]. As a result, MM-OFDMIM outperforms the DM-OFDM scheme as well as all OFDM-IM-related schemes in terms of

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SE and BER performance. Information security is a crucial concern in wireless communication networks because of the wireless medium's broadcast nature. Traditional security methods focus on the top layers, which must handle complicated computations and significant overhead [16], [17].

The family of communication systems that consider transmitting entities other than amplitudes, frequencies, and phases to be information carriers is explicitly referred to as "IM" systems. Theoretically, any kind of communication can be viewed as a specific instance of instant messaging. A new wave of alternative digital modulation schemes has started since the introduction of spatial modulation (SM) and OFDM-IM concepts in the influential works of [18] and [19] in 2008 and 2013, respectively. Early attempts to investigate the potential of IM-based schemes were made at the beginning of this century.

Security of information was ensured for the spatial modulation (SM) systems by utilizing channel reciprocity in the time division duplexing (TDD) mode. In this instance, the eavesdropper is unaware of the channel state information (CSI), whereas the sender and legal receiver know of it [20–22]. The authors of [23] suggested a data-protecting approach for OFDM-IM systems, which was accomplished by creating an adaptive integrating method and a proportion of subcarrier index selection. Alternative mapping criteria for DSM were presented in [24], which led to a high BER at the eavesdropper.

This wave is currently expanding and accelerating more quickly. Numerous new studies on IM technologies have been published in the literature even as this article was being written, and the text has been updated frequently to give readers the most recent, intriguing findings. A successful communication method over multipath fading channels is chaotic communication, which uses a wideband chaotic signal as the carrier [25]. As a result, spread-spectrum and ultra-wideband communication systems [26â30] are great fits for chaotic communication systems. Over multipath fading or time-varying channels, differential chaos shifts keying (DCSK) with a straightforward auto-correlation receiver (ACR) provides good performance [31].

The remainder of this paper is as follows: Section I, the introduction, and Section II describe the proposed OFDM-IM-based chaotic communication scheme. Section III contains the simulation results and discussion. Finally, Section IV is the conclusion.

II. System model and transmission scheme

Chaos theory is a branch of mathematics and science that studies the behavior of complex systems that are highly sensitive to initial conditions. It explores how small differences in initial conditions can lead to vastly different outcomes over time. The use of chaos in communication systems has gained significant attention due to its ability to improve the security and reliability of data transmission. OFDM-IM-based chaos is particularly suitable for wireless communication systems that are subject to fading and interference.

In this technique, a chaotic signal is generated at the transmitter and is used to modulate the index values of the subcarriers in the OFDM signal. The receiver uses the same chaotic signal to demodulate the subcarrier indices and recover the original data. The use of chaotic signals ensures that the subcarrier indices are unpredictable and secure, thereby improving the security and reliability of the communication system.

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To describe the proposed system, first, we explain the proposed secure index, the transmitter system, and the receiver system. Fig. 1 illustrates the proposed system when random digital bits are input to the system that are split into index and data. Chaotic generators are used in the creation of an index to secure it (a logistic map is used), as well as to modulate data using the DCSK modulation method: OFDM block create, IFFT, CP, and P/S apply, and send throw channel, then the opposite in the receiver to return the data. Table I demonstrates all the parameters used in the proposed system.

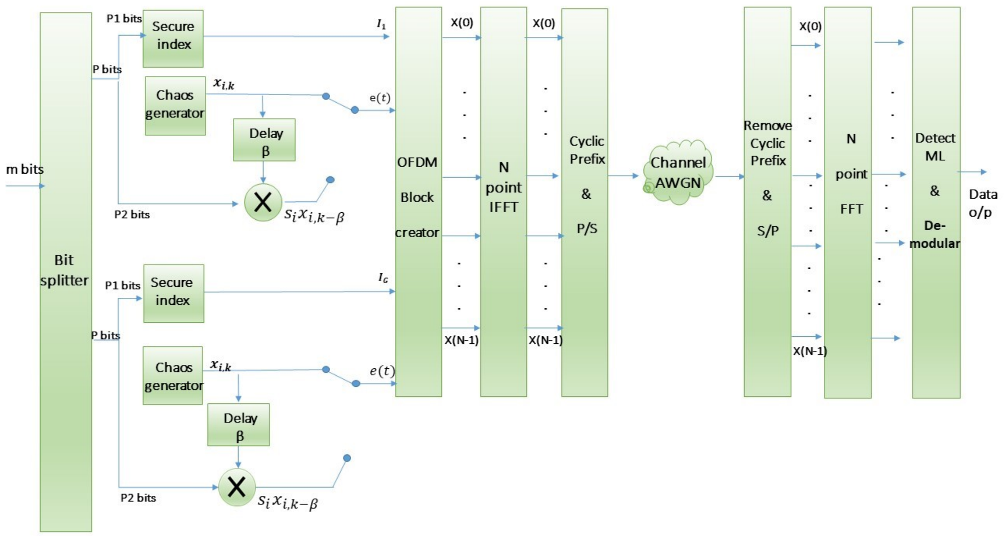

Figure 1: The Proposed System

TABLE I
SYSTEM PARAMETERS

Parameters	Definition
n	Number of subcarriers in each OFDM block
N	OFDM subcarriers
M	Total number of information bits message
p_1	The sum of the bits to which the active indices of each subblock are mapped
p_2	amount of modulation bits expressed as p2 = klog2M
M	Ary modulation size
G	Number of groups
P	P = m/G, the number of bits per group
K	The overall number of subcarriers that are active K=kG
k	Each subblock's active subcarrier count
$I_{(\beta)}$	Chosen indices for the subblock
$s_{(\beta)}$	Modulated subblock symbol
X	Chaotic map

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A. *Proposed Secure Index*

Many types of chaotic generators can be used, but in this paper, we used a logistic map and a Henon map. The logistic map is a population growth model that was first put in [32]. It is derived from the differential equation's continuous form, which is:

$$\frac{dm}{dt} = rm\left(1 - \frac{m}{k}\right) \tag{1}$$

Where k is the carrying capacity and r is the rate of highest population growth (i.e., the most severe population that can be sustained). The differential mathematical expression is then obtained by describing x = m/k and dividing both sides by k:

$$\frac{dx}{dt} = rx(1 - x) \tag{2}$$

The discrete version in the form of a differential equation is described as:

$$x_{n+1} = rx_n(1 - x_n) \tag{3}$$

Where x_n is a number between zero and one and r is in the interval [3.96, 4].

Also, another chaotic map called the Henon map was used, which maps a point of (x_n, y_n) as in the Eqs. (4) and (5), and any change in the bifurcation of maps a and b gives different results.

$$X_{n+1} = 1 - aX_n^2 + bY_n \tag{4}$$

$$Y_{n+1} = X_n \tag{5}$$

The main steps to generate the proposed secure index based on chaotic signals are as follows:

- **Step 1:** Generate a chaotic sequence: A chaotic sequence is generated by applying a chaotic map with an initial condition. The initial condition can be chosen randomly or based on some predetermined criterion. Examples of chaotic systems that can be used include the Lorenz system, the Logistic map, and the Henon map.
- **Step 2:** Quantize the chaotic sequence: The chaotic sequence generated in step 1 is quantized to create a binary sequence. The quantization process maps the continuous chaotic sequence onto a discrete sequence of bits between [0-3].
- **Step 3:** Convert the value from Step 2 to a 2D matrix with size 2×4, where p1 =2, and n=4 and k=2.
- **Step 4:** Discard the row with repeated values from Step 3.
- **Step 5:** Select a secure index matrix from the matrix in Step 4 to modulate the carrier signal.

- **Step 6:** Modulate the carrier signal: The carrier signal is modulated with the index sequence generated to create the SIM signal.
- **Step 7:** Transmit the SIM signal: The SIM signal is transmitted over the wireless channel to the receiver.
- **Step 8:** Receive and demodulate the SIM signal: The SIM signal is received and demodulated at the receiver using the same chaotic system that was used to generate the key.

The details of the proposed secure index mapping based on chaotic are shown in Fig. 2.

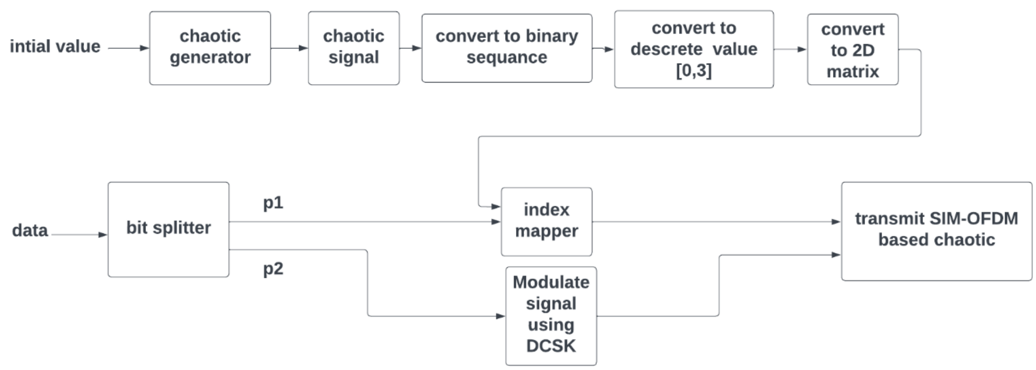

Figure 2: The Proposed Secure Index Mapping Based on Chaotic

B. *The architecture of the transmitter*

The division of an OFDM block of N subcarriers into G subblocks, each having n subcarriers m bits are equally divided into g groups at each instant.

$$m = \begin{bmatrix} b_{1,1} & b_{1,2} & \dots & b_{1,N} \\ b_{2,1} & b_{2,2} & \dots & b_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ b_{G,1} & b_{G,2} & \dots & b_{G,N} \end{bmatrix} \tag{6}$$

Where b is a bit, and each bit has a size of $p = \frac{m}{g}$bits. Since each group is processed using the same procedure, we will use the g^{th} group as an example in this section, where 1, 2, and G. To use two separate modulation techniques, we split these p information bits into two halves. The index selector chooses the ASP of the subblock based on the lookup table and the input bits for the first part, which includes the p_1 bits and is known as the secured IM bit sequence. On both the transmitter and receiver sides, a look-up table of size c is made. This look-up table delivers the corresponding indices for the outgoing p_1 bits for each subblock at the transmitter and does the opposite at the receiver, assuming the subcarriers are ordered ascendingly, which is given by:

$$I^{(\beta)} = \{i_1^{(\beta)}, \dots, i_k^{(\beta)}\} \tag{7}$$

In the proposed system I is equal to:

$$I = \begin{bmatrix} I_{1,1} & I_{1,K} \\ I_{2,1} & I_{2,K} \\ \vdots & \vdots \\ I_{N,1} & I_{N,K} \end{bmatrix} \quad (8)$$

Where $I_{(\beta)}$ with K = 1...k
And

$$p_1 = \lfloor \log_2 C(n,k) \rfloor \quad (9)$$

Where $\lfloor . \rfloor$ are the floor operation and $C(n,k)$ shows the binomial number where i_j^β, i_k^β, and $j \neq k$. An example of ASPs is given in Table II.

TABLE II
ASPS LOOKUP TABLE WITH (4, 2) PARAMETERS AND CHAOTIC INITIAL VALUE OF 0.4

Bits	ASPs
00	$\{2,3\}$
01	$\{2,1\}$
10	$\{0,2\}$
11	$\{3,0\}$

Table II is an example of an ASPs lookup table with (4,2) parameters where the initial value of the chaotic map x is equal to 0.4 at the transmitter and receiver. Every change in the initial state of the chaotic map leads to changes in all index tables. In Table III, the initial value of the chaotic map x is equal to 0.4 at the transmitter and 0.400001 at the receiver. The lookup table for an index is shown below:

TABLE III
ASPS LOOKUP TABLE WITH (4, 2) PARAMETERS AND CHAOTIC INITIAL VALUE OF 0.400001

Bits	ASPs
00	$\{2,3\}$
01	$\{3,1\}$
10	$\{2,0\}$
11	$\{3,2\}$

Table III is an example of an ASPs lookup table with (4,2) parameters where the initial value of the chaotic map x is equal to 0.4 at the transmitter and 0.400001 at the receiver. To generate p2, the data symbol vector is produced by the second portion, which consists of the following symbol bits:

$$p2 = k \log_2 M \quad (10)$$

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And

$$S^{(\beta)} = \left[s_1^{(\beta)}, \ldots, s_k^{(\beta)}\right]^T \tag{11}$$

$$S = \begin{bmatrix} S_{1,1} & S_{1,p2} \\ S_{2,1} & S_{2,p2} \\ \vdots & \vdots \\ S_{N,1} & S_{N,p2} \end{bmatrix} \tag{12}$$

Where $\mathbf{S}_k^{(\beta)} \in S$ and $K = kg$ is the total number of active subcarriers ($K = 1, \ldots, k$), and S is the modulation of DCSK. Since there are $C(n, k)$ possible realizations of $\mathbf{I}^{(\beta)}$, as a result, the transmitted signal, $e(t)$, is equal to:

$$e(t) = \begin{cases} x_{i,k}, & \text{for } 1 < k \leq \beta \\ s_i x_{i,k-\beta}, & \text{for } \beta < k \leq T \end{cases} \tag{13}$$

Where T is the bit duration. For transmission, the frequency-domain OFDM-IM signal is converted into the time domain as follows:

$$X_T = \frac{N}{\sqrt{k}} \text{IFFT}\{X_F\} = \frac{1}{\sqrt{k}} W_N^H X^F \tag{14}$$

W_N: Discrete Fourier transform (DFT) matrix with $w_N^H W_N$ After Inverse Fast Fourier transform (IFFT), appending cyclic prefix (CP) of length N_{cp}, which is as follows:

$$X_{(T,cp)} = X_T(N - N_{cp} + 1) \ldots X_T(N)^T \tag{15}$$

Placed at the start of X_T. To prevent inter-block interference, it should be noted that the CP length, denoted by Ncp, must be greater than the length of the channel impulse response (CIR), denoted by v [33, 34]. The signal is transferred in parallel with serial and digital-to-analog conversion.

C. *The architecture of the Receiver*

The following equivalent I/O relation in the frequency domain [35] is presented following the removal of the CP from the received signal at the receiver and the completion of N-point FFT:

$$y = Hx + n \tag{16}$$

Where:

$$y = \left[y_1^T, y_2^T, y_3^T, \ldots, y_n^T\right]^T \tag{17}$$

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and H is the channel matrix:

$$H = \left[h_1^T, h_2^T, h_3^T, \ldots, h_n^T\right]^T \tag{18}$$

The channel matrix H has complex Gaussian random variables with zero mean and unit variance as its elements, i.e., h(n) $\sim CN(0,1)$. The additive white Gaussian noise (AWGN) vector is denoted by n.

The Maximum Likelihood (ML) detector [36] is used at the receiver to decode the g^{th} subblock after switching from serial to parallel transmission and deleting the cyclic prefix (CP). This detector explores all conceivable subcarrier index combinations and signal constellation points to examine all realizations.

Each subblock's constellation symbols and active indices are jointly decided by:

$$\left\{\left(\hat{I}^{(\beta)}, \hat{S}^{(\beta)}\right)\right\} = \arg\min \sum_{\Gamma=1}^{k} \left| y_F^{(\beta)} - h_F^{(\beta)}\left(i_{(\beta,\Upsilon)}, s_\beta(\Upsilon)\right)\right|^2 \tag{19}$$

where $y_F^{(\beta)}$(€) and $h_F^{(\beta)}$(€) for €= 1, $\ldots$, n are the received signals and the corresponding fading coefficients for β. The total number of metric calculations performed here is cM^k since $I^{(\beta)}$ and $S^{(\beta)}$ have c and M^k different realizations, respectively.

III. Simulation Result

The system parameters that were used are listed in Table IV.

TABLE IV
SIMULATION PARAMETERS

Parameter values	Chaotic with OFDM-Im
N	4
Modulation type	DCSK
N	64
Alphabet size, m	2
K	2

Both the plot for the x-sequence with initial conditions of $(x_0) = (0.8000000)$ and the plot for the x-sequence with initial conditions of (x_0) are shown in Fig. 3, which highlights the sensitive dependency of initial conditions (0.8000001). Despite the 19 iterations and a 0.000001 difference in one of the initial conditions, it is clear that the two sequences are very different.

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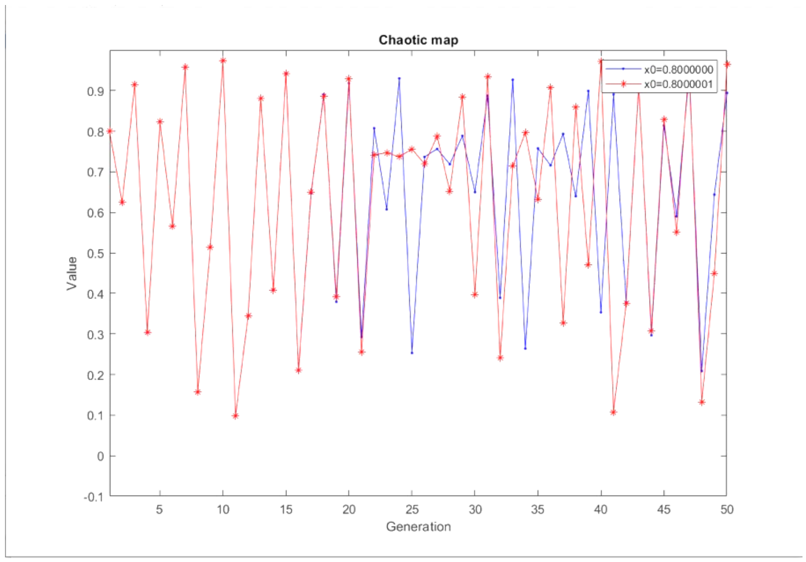

Figure 3: Difference between the initial values of the chaotic map

Fig. 4 displays the results of plotting the logistic iteration parameter's execution as a function of r. The stable state was found to split into a bifurcation and two different occasional patterns when r was high. When r was low, the map settled into a consistent state after a few cycles. From there, the structure is segregated into a four-state intermittent structure and, finally, an eight-state structure. In the included estimation of r, the map sequence enters the chaotic zone, which exhibits unexpected behavior.

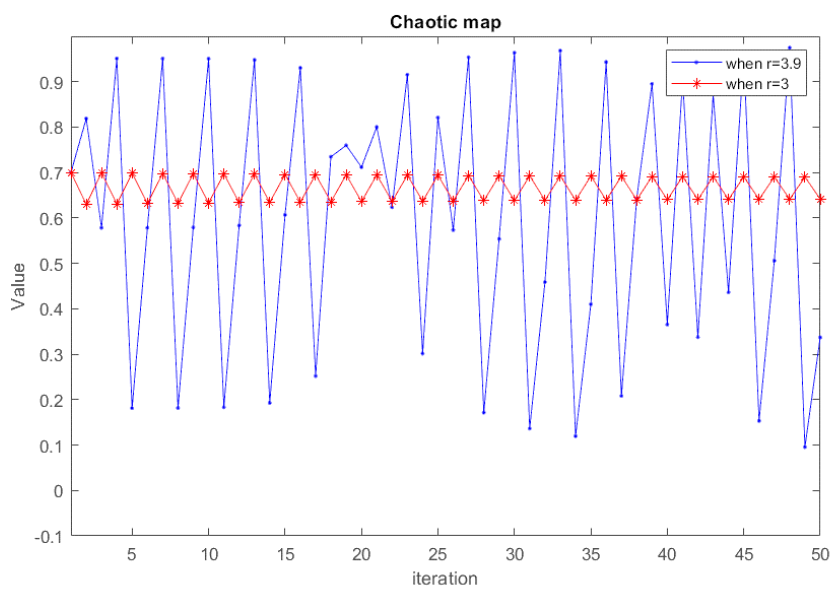

Figure 4: Change in r value effect

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The security level is different in index modulation-based security; the eavesdropper must know the initial value of the system and the index table to know the cipher text.

Fig. 5 explains the Bit Error Rate (BER) when using the logistic map with the same initial condition in the transmitter and receiver equal to 0.800000. We get 30 dB at 10^{-4}, but in Fig. 6, when using a different key with an initial value equal to 0.800000 in the transmitter and 0.8000001 in the receiver, we get a result of 30 dB at 10^{-1}.

To verify the security of the proposed system based on chaos, Brute-force attacks should not be practicable due to the size of the key space. The 64-bit double-precision number has a computational precision of around 2^{100}, according to the IEEE floating-point standard [37]. The keys of the logistic chaotic system include x and r. So, the size of the key of the proposed system is $2^{52} \times 2^{52} = 2^{104}$, which is resistant to a brute-force attack.

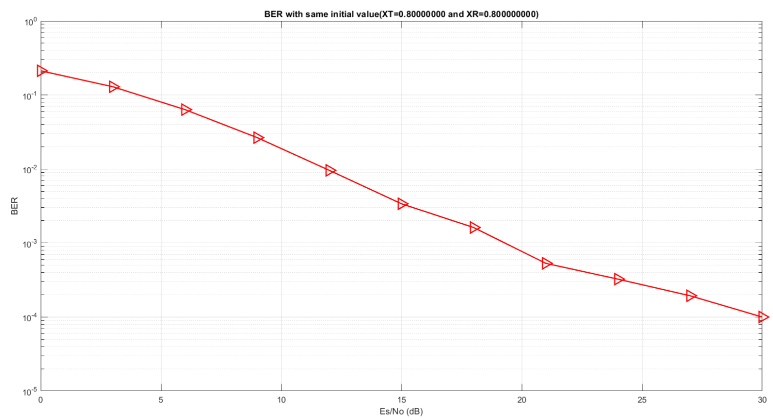

Figure 5: BER of the secure index-based logistic map with x=0.800000 in the transmitter and receiver

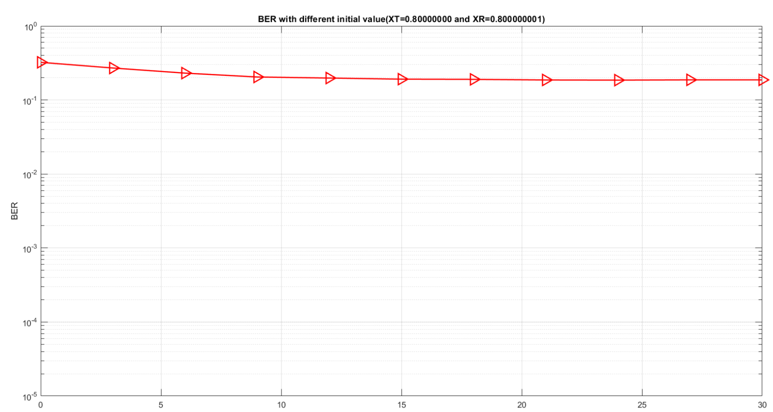

Figure 6: BER of the secure index-based logistic map at x=0. 800000 at the transmitter and 0.8000001 in the receiver

Fig. 7 compares the Bit Error Rate (BER) performance of the proposed system with that of conventional SIM-OFDM

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under Additive White Gaussian Noise (AWGN) and frequency-selective Rayleigh fading channel conditions. The proposed OFDM-IM-based chaos achieves a 3 dB performance gain over SIM-OFDM for both channels.

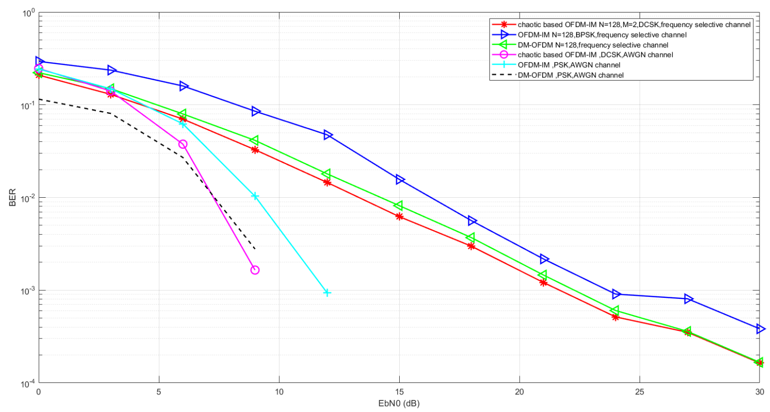

Figure 7: Comparison between DM-OFDM, CHAOTIC-based OFDM-IM, and OFDM-IM in AWGN and fading channels

Fig. 8 shows a comparison of the performance between traditional Binary Phase Shift Keying (BPSK) modulation and Dual-Channel Shift Keying (DCSK) modulation techniques under two cases: $n = 4$, $M = 2$, and $k = 2$ while considering the frequency-selective fading channel.

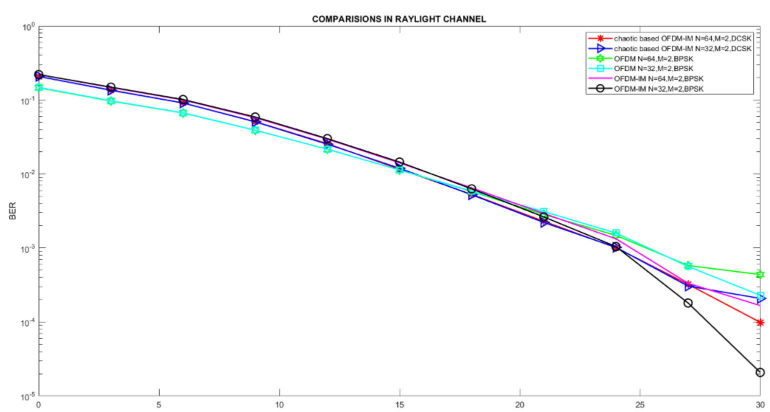

Figure 8: BER performance of OFDM, OFDM-IM using BPSK, and OFDM-IM using DCSK chaotic modulation in frequency selective fading channel with N=64, 32

Figure 9 shows $a = 1.4$ and $b = 0.3$ in the first step and $a = 1.7$, $b = 0.1$ in the second step using the Henon map. The keys of the Henon chaotic system include x, y, a, and b, so the size of the key using the Henon map is $2^{52\times4} = 2^{208}$, which is large enough to resist all kinds of brute-force attacks.

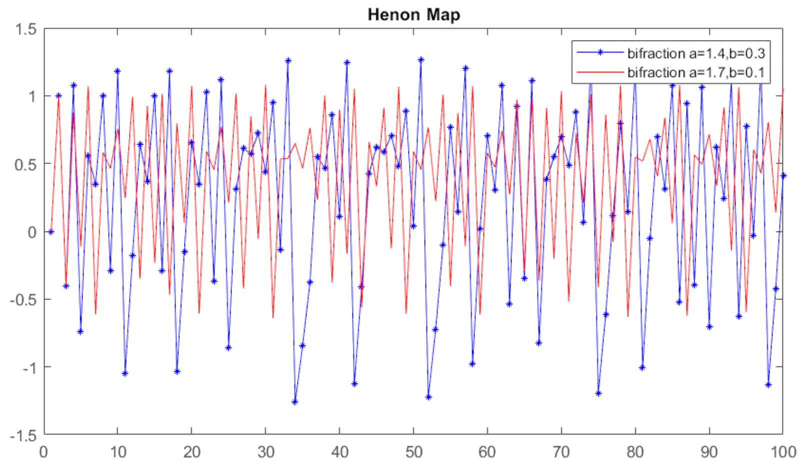

Figure 9: Henon map bifurcation

IV. Conclusion

To enhance the achievable security rate, we have proposed an Orthogonal Frequency Division Multiplexing (OFDM) system with index modulation that utilizes chaotically modulated signals in each subcarrier. Based on the initial value of the chaotic system, which must be synchronized between the transmitter and receiver to obtain the information bit for secure index modulation, the index modulation bits are transformed by the transmitter into a set of admissible mode permutations that are concealed from eavesdroppers. As the modulation data sequence and the secret key are generated using a chaotic system, they exhibit a high degree of unpredictability. The Index Modulation (IM) technique based on chaotic systems offers enhanced security compared to traditional encryption schemes. Moreover, the SIM technique is highly efficient in terms of computational complexity and is resilient against brute-force attacks.

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