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Original Article

BER Analysis of Chaos-Based Digital Communication Schemes under Multipath Fading Channel

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Abstract - *This study investigates the efficiency of different digital communication methods by employing a discrete 2D chaotic signal as the carrier. It focuses on evaluating their noise tolerance in multipath fading channels. The goal is to assess channel performance across diverse fading conditions using various modulation techniques. The analysis examines the BER and SNR characteristics of AWGN, Rayleigh, and Rician fading channels. The findings reveal that Rician channels demonstrably offer significantly superior performance. A comparison table presenting these calculated values is included and discussed. The analysis was implemented using MATLAB code and Simulink.*

Keywords - *Chaos-based communication schemes, Digital modulation/demodulation, BER analysis, Fading channel.*

1. Introduction

Chaos-based secure communication has attracted significant attention due to its inherent randomness and unpredictability compared to conventional methods relying on periodic signals. While existing research has explored various chaotic systems and modulation techniques, particularly Differential Chaos Shift Keying (DCSK) and its variants, there remains a gap in comprehensively evaluating novel systems and methods for improved performance [1].

This paper addresses this gap by introducing a novel discrete 2-D chaotic system specifically designed for enhanced security and unpredictability in communication systems. We compare this system to existing ones, highlighting its unique features, such as [2, 3]: Increased dimensionality: The 2-D nature offers additional degrees of freedom for modulation and encryption, potentially leading to improved security and resistance to attacks.

Enhanced unpredictability: The specific design of the system aims to achieve greater complexity and aperiodicity, making it harder to predict and break down the signal. Tailored for communication: The system is designed with communication applications in mind, considering factors like ease of implementation and compatibility with existing modulation techniques.

Furthermore, we go beyond DCSK and evaluate a broader range of digital modulation and demodulation techniques suitable for the proposed 2-D chaotic system. This includes techniques not typically explored in previous studies, such as: High-order modulation schemes: These exploit the broader bandwidth of the chaotic signal for increased data rate and potential spectral efficiency.

Multi-carrier modulation: This allows for parallel transmission of data streams, improving robustness against fading and interference.

Nonlinear demodulation techniques: These leverage the inherent nonlinearity of the chaotic signal for improved performance in noisy channels.

Through a comprehensive comparative analysis, we evaluate the performance of these techniques against noise and Bit Error Rate (BER) in multipath fading channels. We compare our results with existing studies using DCSK and other chaotic systems, highlighting the advantages of our proposed system and chosen techniques.

This paper contributes to the field of chaos-based secure communication by Introducing a novel 2-D chaotic system with enhanced security and unpredictability. Evaluating a broader range of modulation and demodulation techniques for improved performance, providing a comprehensive performance analysis in multipath fading channels. By addressing the limitations of existing research and showcasing the potential of our proposed system and techniques, we aim to advance the development of secure and reliable communication systems.

2. Chaotic System Implementation

The proposed communication system relies on a 2-D discrete chaotic system with an expanded set of control parameters. This deliberate design choice amplifies the system's complexity, leading to a more intricate and unpredictable chaotic signal.

Consequently, the enhanced security of the communication channel is fortified against unauthorized access and interference. The state equations of the chaotic system are presented as follows:

$$x_{n+1} = a\, x_n - x_n\, y_n \quad (1)$$

$$y_{n+1} = b\, x_n - c\, y_n \quad (2)$$

Where, x_n and y_n are state variables, a=2.3 and b=0.4 are constant parameters and c=0.8 is a control parameter in Equations 1 & 2. Matlab Simulink model of the system is shown in Figure 1.

Figure 2(a) presents the system's time series waveform, while Figure 2(b) illustrates its phase portrait. The bifurcation diagram and its corresponding Lyapunov exponent are depicted in Figure 3. The maximum Lyapunov exponent of c is in the range (0.8,2) when the system's control parameters a=2.3 and b=0.4 are specified.

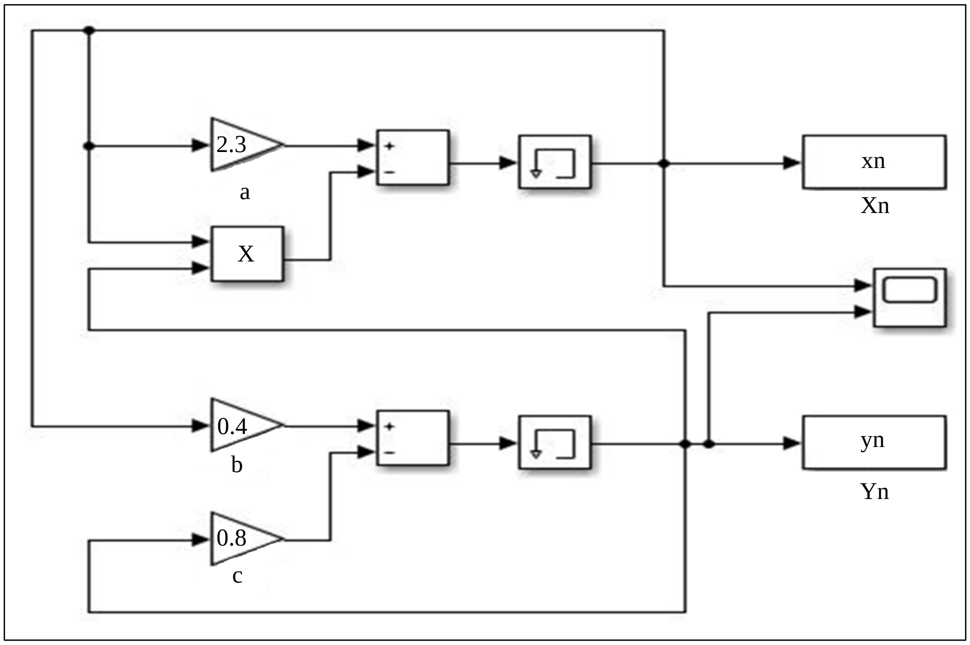

Fig. 1 MATLAB Simulink model of the chaotic system with control parameter a=2.3, b=0.4, and c=0.8

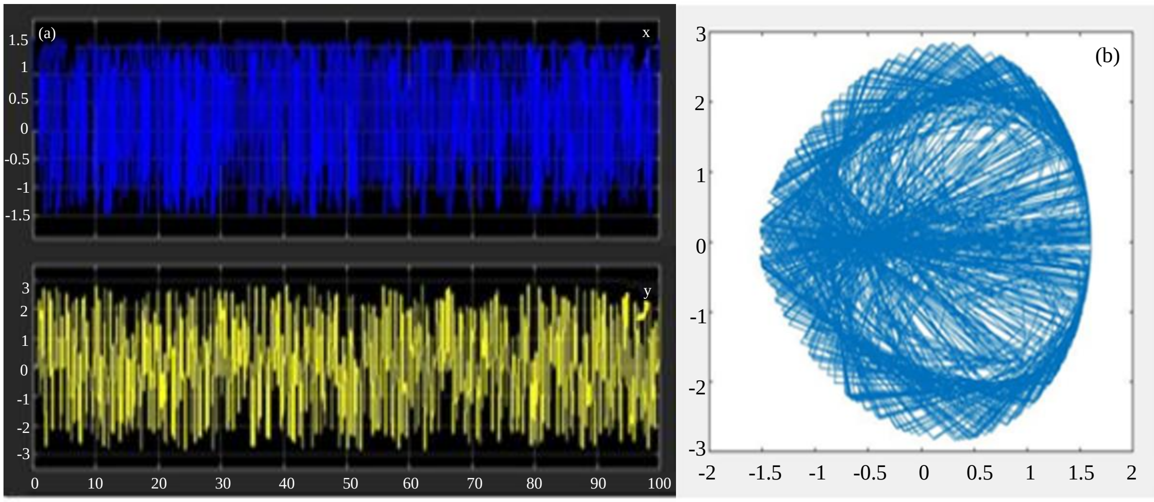

Fig. 2(a) x and y time-series waveform in ms, and (b) x-y phase portrait.

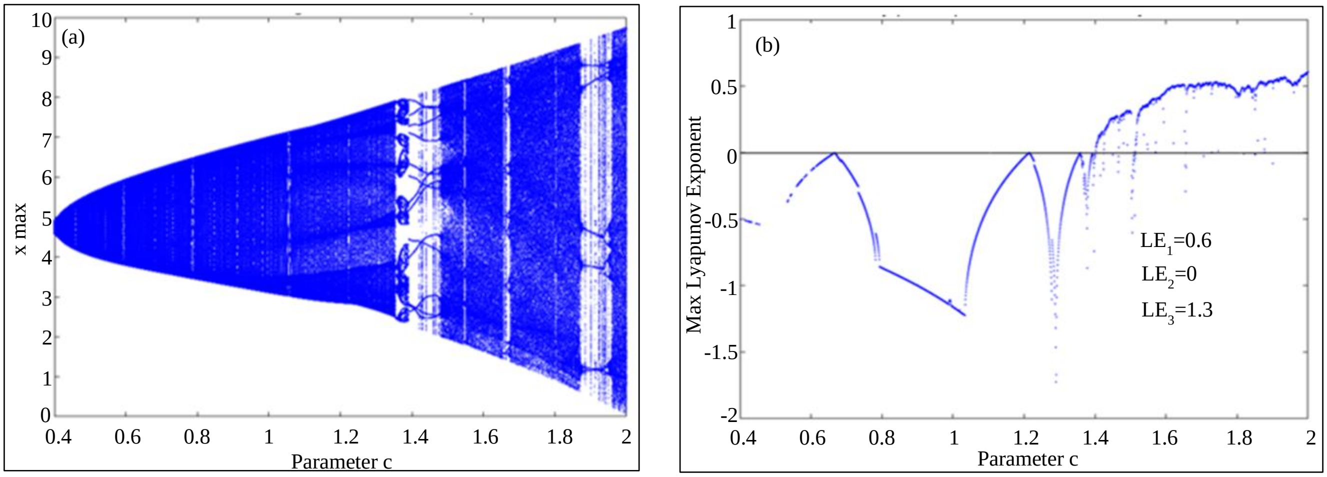

Fig. 3(a) Bifurcation diagram, and (b) Lyapunov exponent for varying parameter c and constant parameter a=2.3 and b=0.4.

Analysis reveals an irregular and random waveform, with the bifurcation diagram depicting a transition to chaotic behaviour through period doubling. The positive maximum Lyapunov exponent further solidifies this, confirming the chaotic dynamics within the model.

3. Chaotic Modulation Schemes

Recent years have seen a surge in the development and modification of various chaotic modulation schemes, driven by breakthroughs in both analog and digital approaches for both coherent and non-coherent receivers [4-7]. While early work by Pecora and Carol [8] laid the groundwork for synchronization in analog modulation schemes with coherent receivers [4, 6, 9], subsequent analysis exposed its sensitivity to channel noise, parameter mismatch, and signal distortion.

Later, various digital modulation schemes using non-coherent receivers [10] were introduced, which showed more advantageous properties than analog modulation schemes, such as high capacity data transmission, better noise immunity, error control, ability to encrypt data, flexible modulation and demodulation and many more. This paper examines three chaos-based digital communication schemes: Differential Chaos Shift Keying (DCSK), Frequency-Modulated DCSK (FM-DCSK), and Noise Reduction DCSK (NR-DCSK). To illustrate their implementation, Figure 4 presents a block diagram of a typical chaos-based communication system [10].

3.1. Differential Chaos Shift Keying (DCSK)

Kolumban et al. [11] introduced a modulation technique called DCSK that eliminates the need for synchronization to recover the message signal. Its operation in the form of the block diagram is demonstrated in Figure 5 [10]. In this scheme, each bit is represented by two samples: a reference signal and an information-carrying signal.

To transmit a bit value of 1, the reference signal is repeated. For a bit value of -1, the reference signal is followed by its inverted version. The receiver correlates these two samples and makes a decision based on a threshold [3]. The mathematical expression for the transmitted signal is given by:

$$s(t) = \begin{cases} c(t), & 0 \le t \le \frac{T_b}{2} \\ \pm c\left(t - \frac{T_b}{2}\right), & \frac{T_b}{2} \le t < T_b \end{cases} \qquad (3)$$

Where T_b is the bit duration, and c(t) is the chaotic signal.

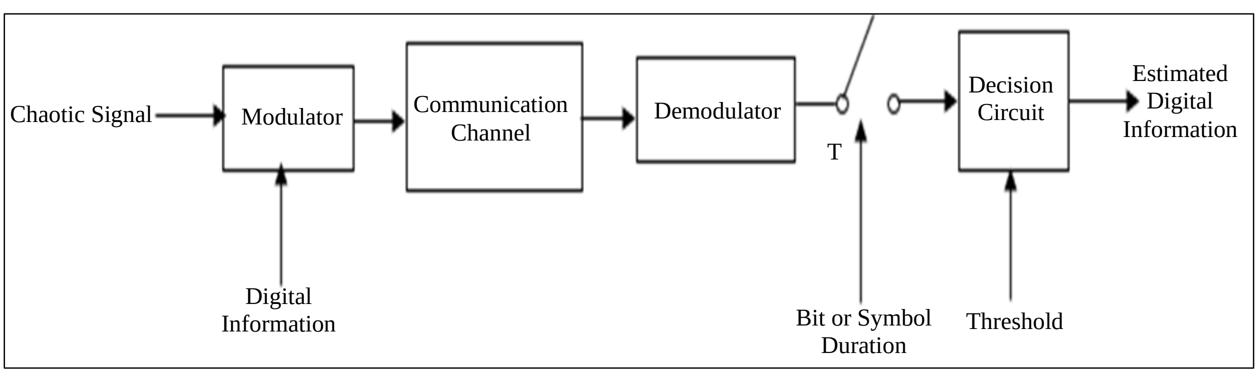

Fig. 4 The block diagram of a chaos-based digital communication system

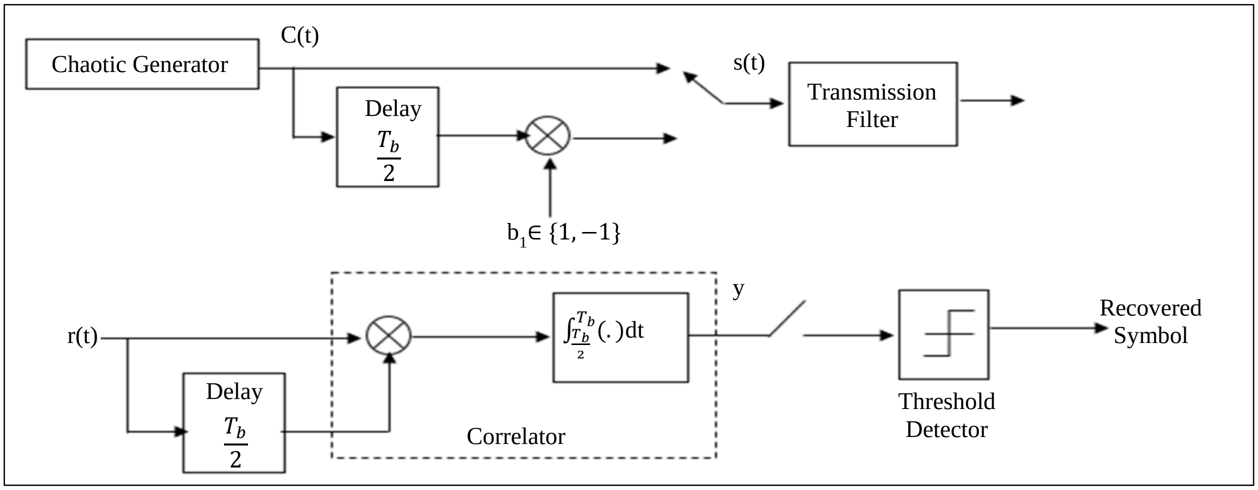

Fig. 5 DCSK system model

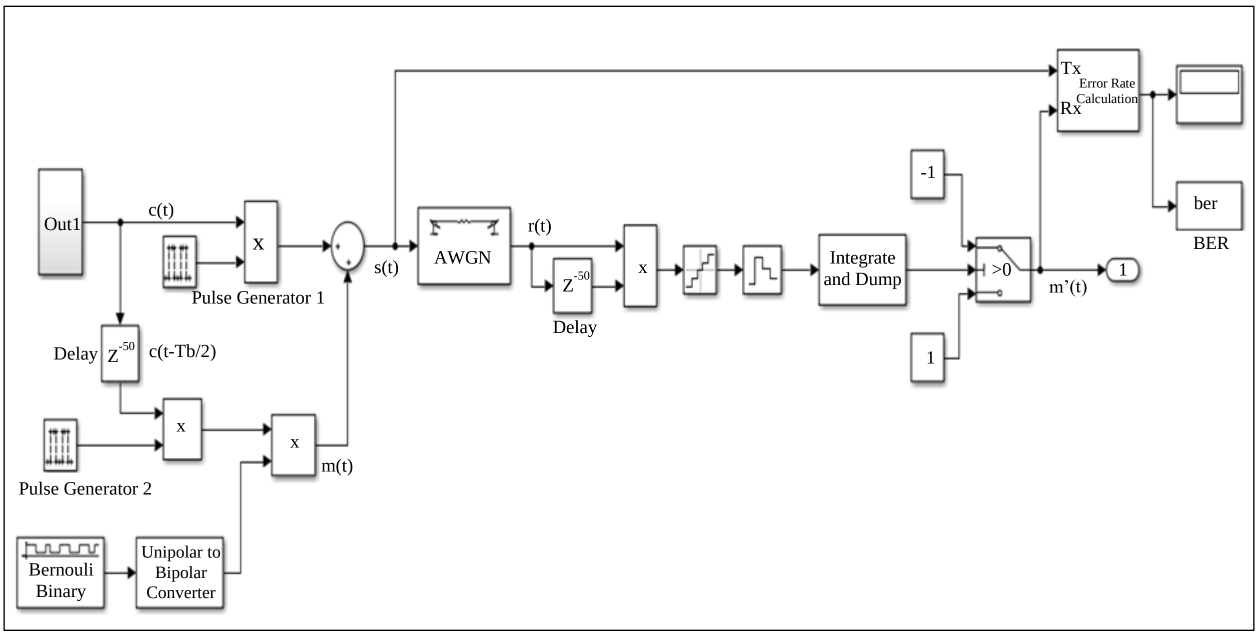

Fig. 6 MATLAB-Simulink block of the DCSK system

The MATLAB-Simulink implementation of the DCSK system is presented in Figure 6, and its output is in Figure 7. Assume that every data bit consists of 100 chaotic samples and the spreading factor is defined as β (i.e., β = 100). As a result, a delay block with 50 samples (z^{-50} block) is employed to achieve half data duration delay (i.e., $\frac{T_b}{2}$).

Using a unipolar Bernoulli source, random data is generated, which is then transformed into a bipolar format to perform multiplication operations with the chaotic signal.

3.2. Frequency Modulated Differential Chaos Shift Keying (FM-DCSK)

Instead of utilizing chaotic signals like DCSK, FM-DCSK combines frequency modulation with DCSK principles to achieve better noise resistance while maintaining consistent energy per bit [9, 12]. As shown in Figure 8, the information bit in FM-DCSK is split into two parts: a reference sample and a data-carrying sample [13].

Notably, the input to the modulator is the FM-modulated signal, not the original chaotic signal. MATLAB Simulink block of FM-DCSK is shown in Figure 9, and its output in Figure 10. The spreading factor β (i.e., β = 100) is utilised with the AWGN channel.

As a result, a delay block with 50 samples (z^{-50} block) is used to achieve half data duration delay (i.e., $\frac{T_b}{2}$). As the information signal, the Bernoulli Binary source is used to generate random data.

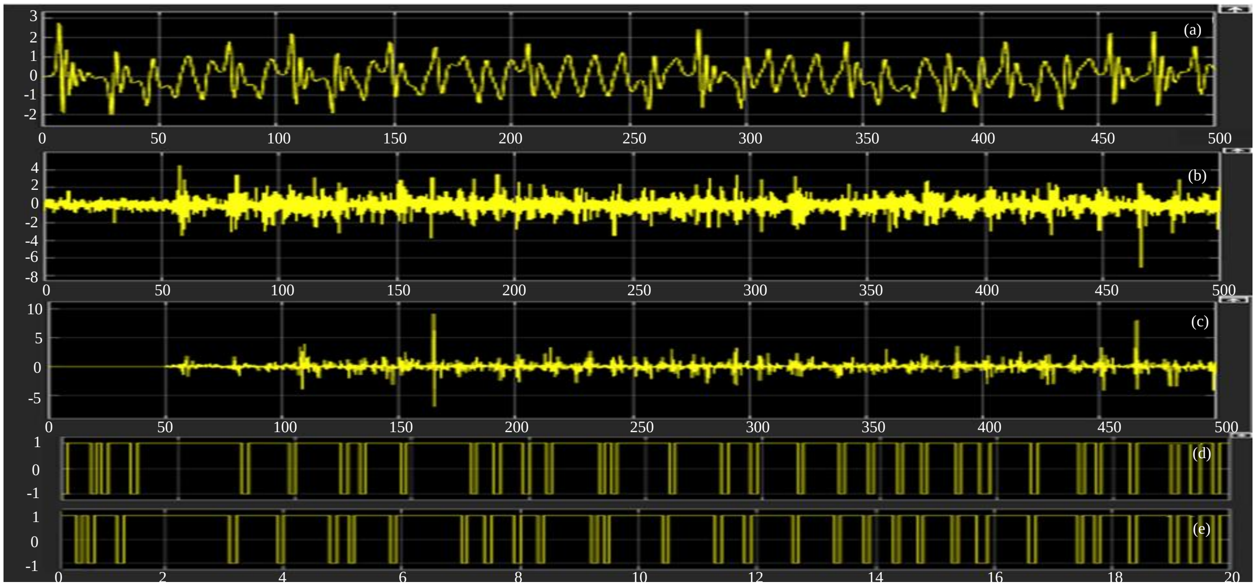

Fig. 7 Differential Chaos Shift Keying (a) Chaotic signal c(t), (b) Transmitted signal s(t), (c) Correlated signal, (d) Information signal m(t), and (e) Recovered information signal m'(t).

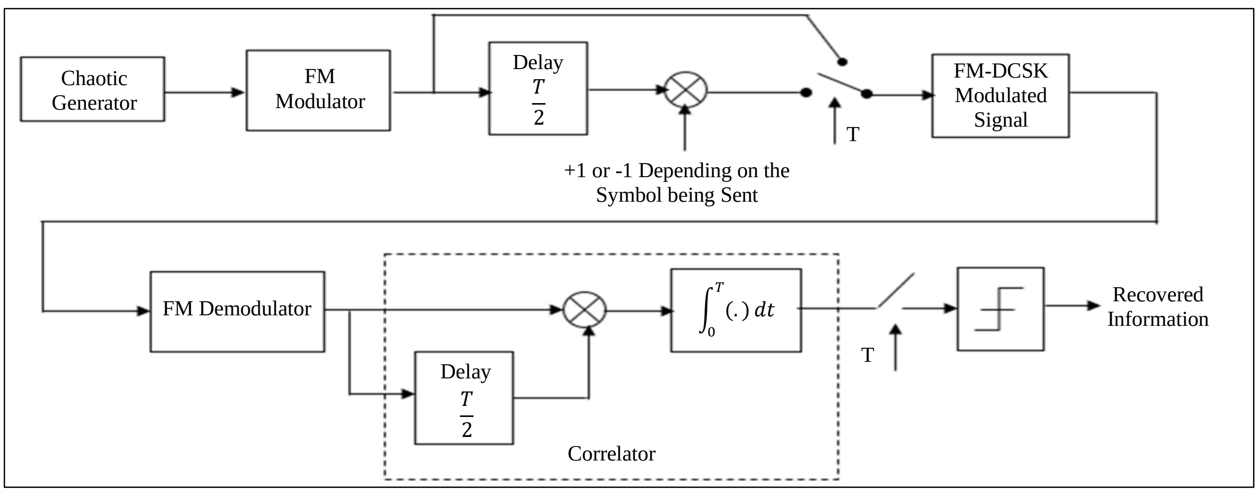

Fig. 8 Block diagram of the FM-DCSK system

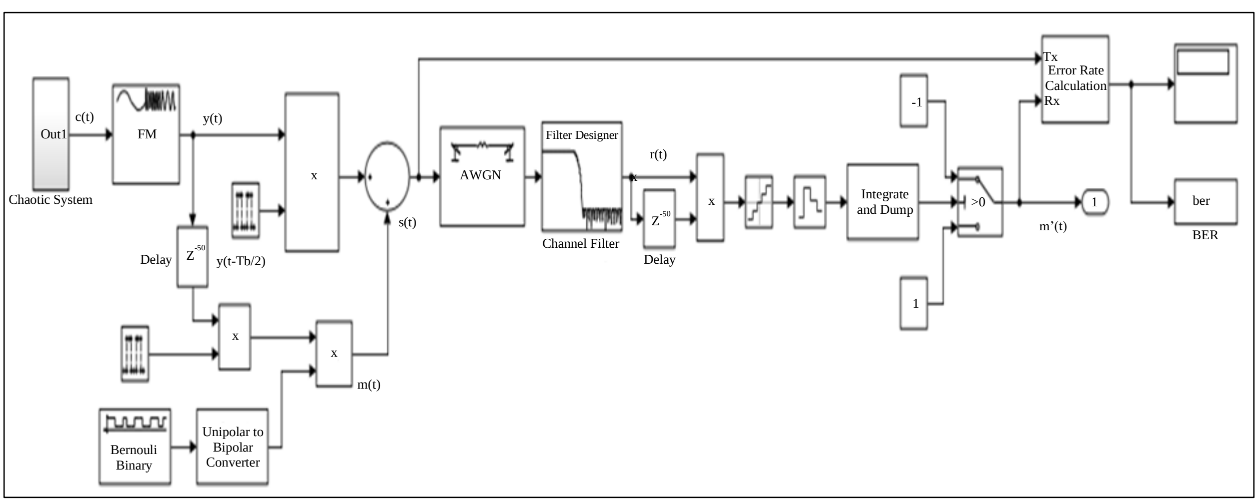

Fig. 9 MATLAB Simulink block of FM-DCSK

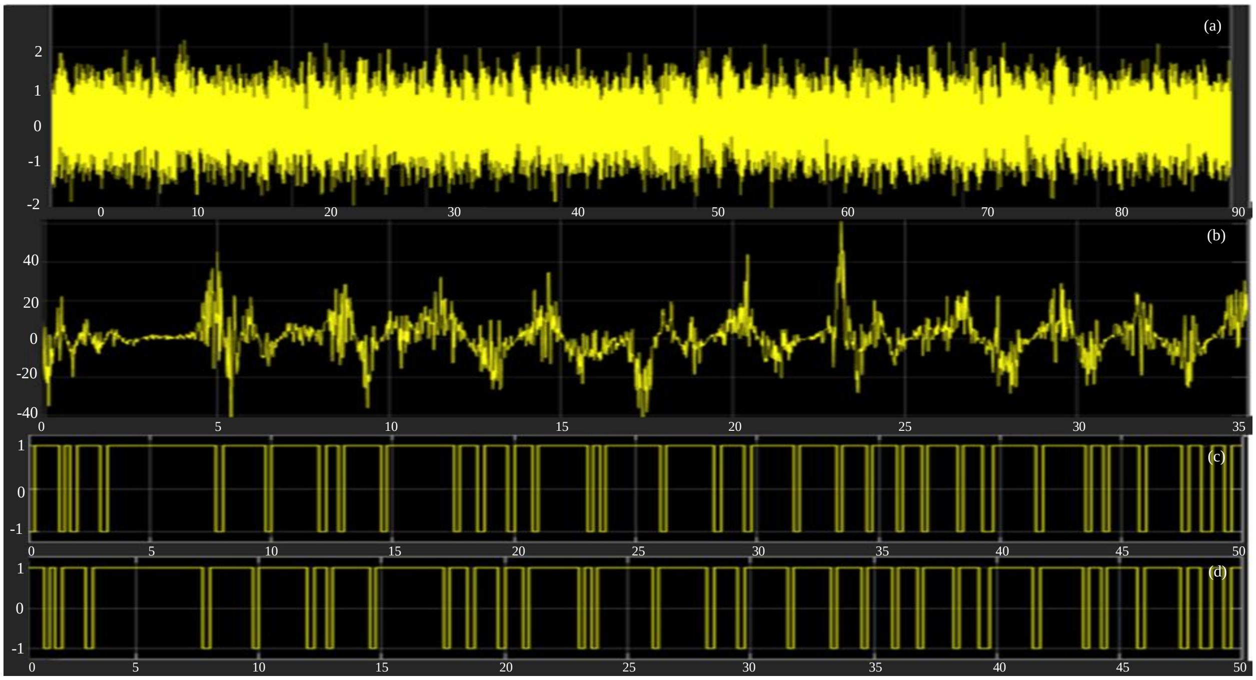

Fig. 10 Frequency Modulated Differential Chaos Shift Keying (a) Transmitted FM-DCSK waveform, (b) Signal after the integrator, (c) Transmitted information, and (d) Recovered information.

3.3. Noise Reduction Differential Chaos Shift Keying (NR-DCSK)

The block diagram of NR-DCSK is shown in Figure 11, where $\frac{\beta}{P}$ different chaotic samples at frequency $f_s = \frac{1}{PT_c}$ per sample is generated by the chaos generator [14]. In the NR-DCSK system, the way data bits are encoded depends on whether a +1 or -1 is being transmitted: To send a +1, the data-bearing sequence is made to match the reference sequence directly.

To send a -1, the data-bearing sequence is constructed as an inverted version of the reference sequence. This encoding scheme is captured mathematically in the expression for the signal $e_{i,k}$ transmitted during the ith bit time interval.

$$e_{i,k} = \begin{cases} x_i\left[\frac{k}{P}\right], & 0 < k \leq \beta \\ b_i x_i\left[\frac{k}{P}\right] - \beta, & \beta < k \leq 2\beta \end{cases} \quad (4)$$

The received NR-DCSK signal corresponding to the i^{th} bit transmission can be written as [14]:

$$r_{i,k} = \propto_1 e_{i,k} + \propto_2 e_{i,k-T} + n_{i,k} \quad (5)$$

Where $e_{i,k}$ is the NR-DCSK transmitted signal and $n_{i,k}$ is additive white Gaussian noise with zero mean and variance $\frac{N_0}{2}$.

MATLAB Simulink block of NR-DCSK is shown in Figure 12 and its output is in Figure 13.

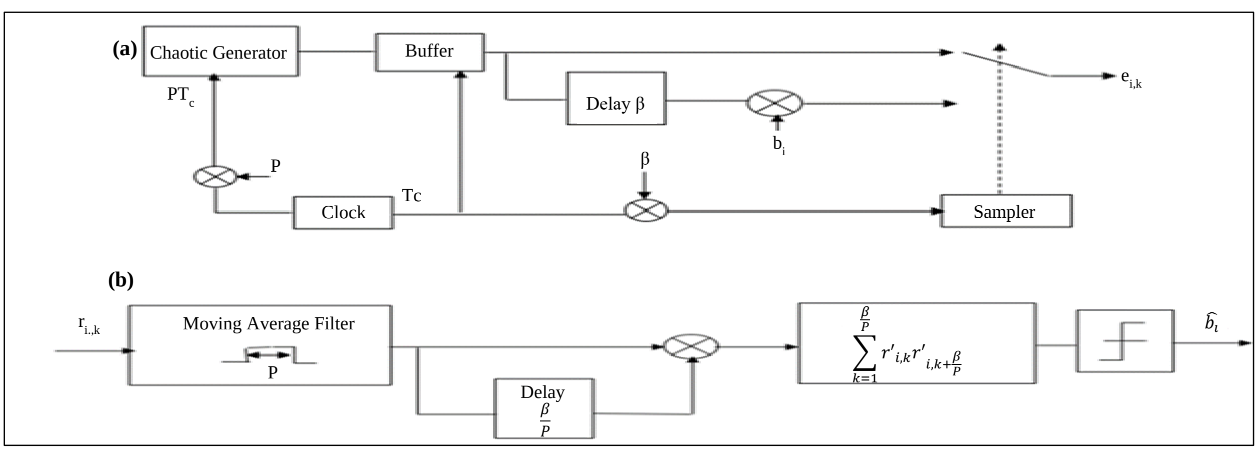

Fig. 11 Block diagram of NR-DCSK communication system (a) Transmitter, and (b) Receiver.

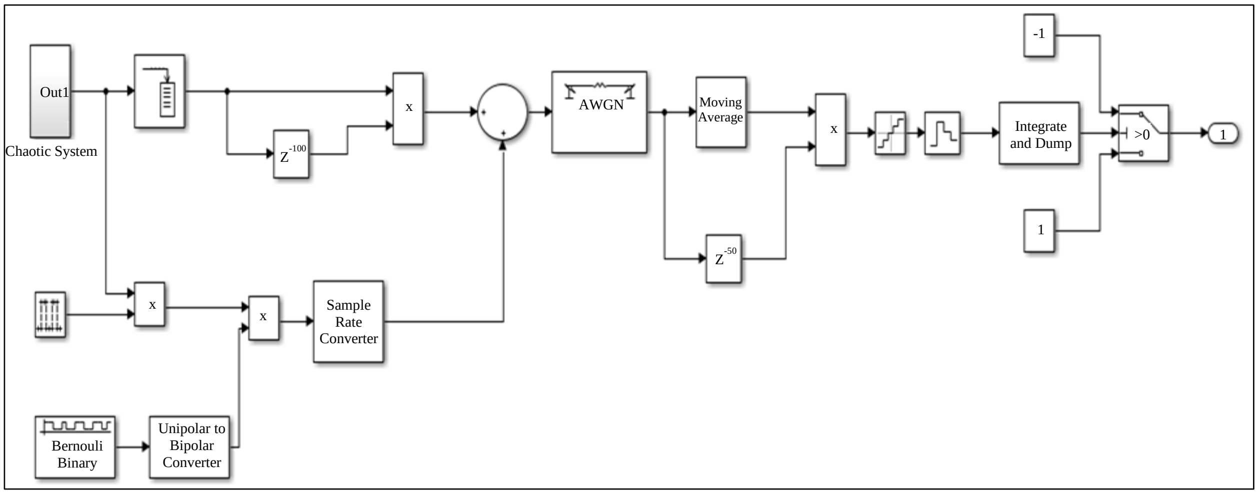

Fig. 12 MATLAB-Simulink block of NR-DCSK

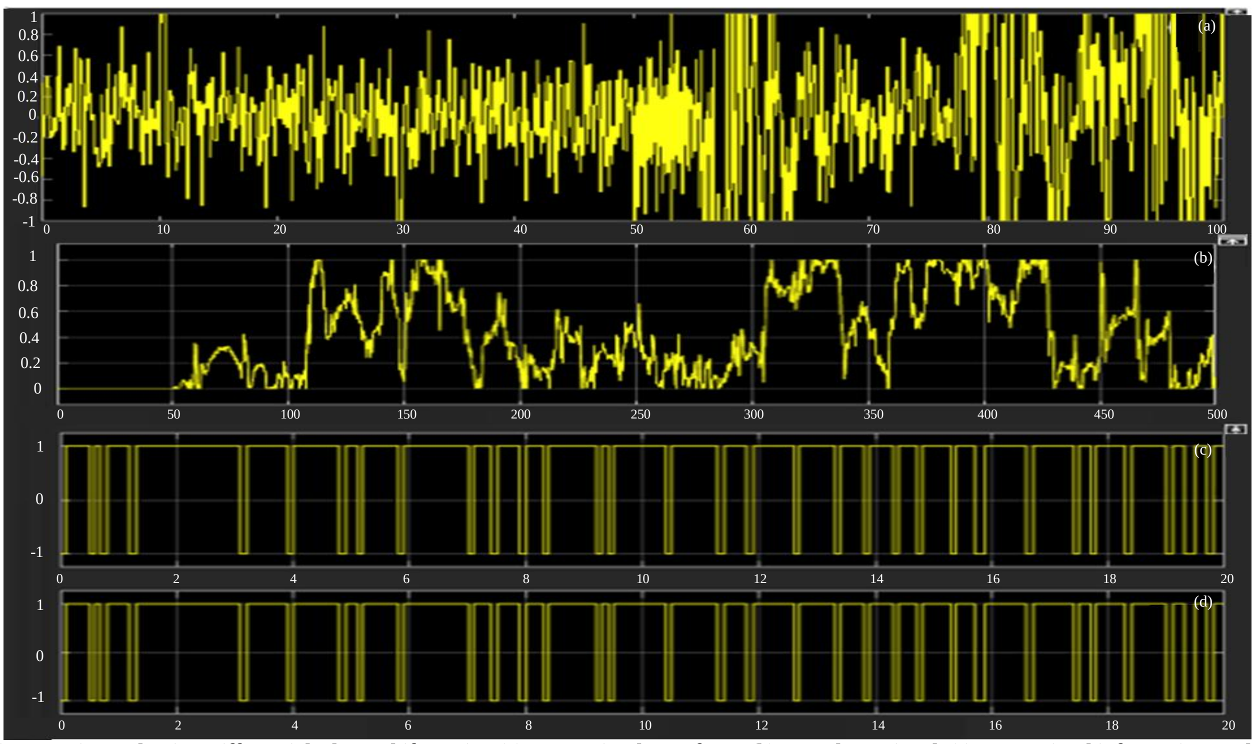

Fig. 13 Noise Reduction Differential Chaos Shift Keying (a) Transmitted waveform, (b) Correlator signal, (c) Transmitted information, and (d) Recovered information.

From the above results, it is seen that the information transmitted is the same as the information received. There is no significant delay seen in the modulation scheme discussed in the paper. Among NR-DCSK, the loss of information in the communication channel may be a few microseconds; hence, it is more secure and efficient.

4. BER Analysis under Multipath Fading Channel

The investigation of the chaos-based communication system is performed under AWGN Channel. A graph of BER in Figure 14 as a function of Eb/No shows a noise performance comparison of various communication schemes. Table 1 gives the BER value of the modulation scheme up to 10dB, indicating that as the value of Eb/No is increased, the BER value is reduced.

From the graph below, it is seen that in order to achieve BER 10^{-3} NR-DCSK require $\frac{E_b}{N_0}$ = 7dB, and DCSK require $\frac{E_b}{N_0}$ = 11dB. The loss in the system performance is about 4dB, which proves that the NR-DCSK system performs better than the other modulation schemes.

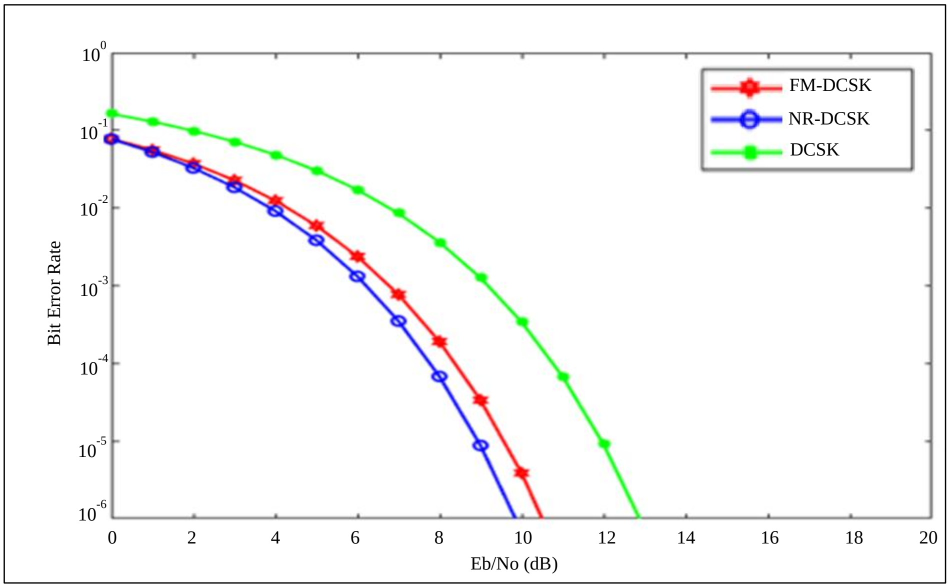

Fig. 14 BER comparison of a modified chaotic system in different modulation schemes

Table 1. Values of BER at different dB for different modulation schemes under AWGN channel

Eb/No (dB)	DCSK	FM-DCSK	NR-DCSK
1	0.84513	0.07853	0.07771
2	0.82337	0.07527	0.07418
3	0.08015	0.07173	0.07010
4	0.07691	0.06739	0.06440
5	0.07365	0.00616	0.00581
6	0.06927	0.00546	0.00513
7	0.06416	0.00046	0.00040
8	0.00573	0.00036	0.00027
9	0.00518	0.00008	0.00006
10	0.00047	0.00006	0.00004

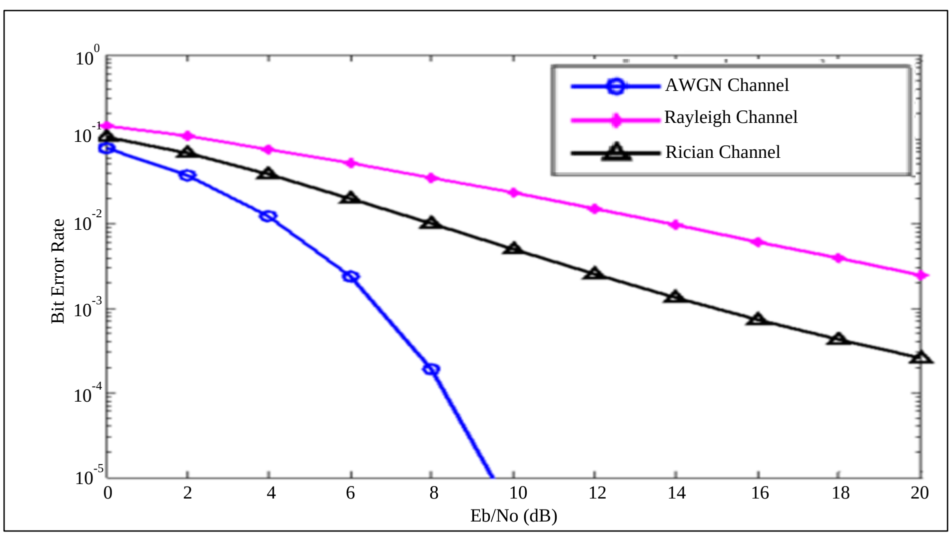

Fig. 15 BER performance of NR-DCSK in AWGN, Rayleigh and Racian fading channel

From the above table, it is seen that the $\frac{E_b}{N_0}$ increases the BER value of NR-DCSK dcreases and is least than the two modulation schemes. The BER graph of NR-DCSK in AWGN, Rayleigh and Racian channels is given in Figure 15.

From the above Figure 15, it is seen that the Racian model provides improved performance compared to the Rayleigh fading model, but is more complex and challenging to use. However, it can be overcome by two parameters of the fading channel, which are the average signal power and the Rician factor.

This model incorporates both deterministic and stochastic elements to represent the channel's energy distribution, with the K-factor influencing the characteristics of the randomness [15]. Therefore, the Rician fading model is a more appropriate choice for wireless communication scenarios. Figure 16 depicts the BER graph of the NR-DCSK scheme in a Rician fading channel with a K-factor varying from 1 to 30.

The Racian K-factor plays a vital role in wireless channels and is described as the ratio of signal power in the Line-of-Sight (LOS) to the scattered power. As evident in Figure 16, increasing the K-factor of the Rician fading channel leads to improved BER performance.

From the Table 2, it is seen that achieving BER 10^{-2}, for K=1, $\frac{E_b}{N_0}$ = 13dB and for K=30, $\frac{E_b}{N_0}$ = 4dB. The system's performance loss is about 9dB, which proves that for higher values of K-factor, it has better performance.

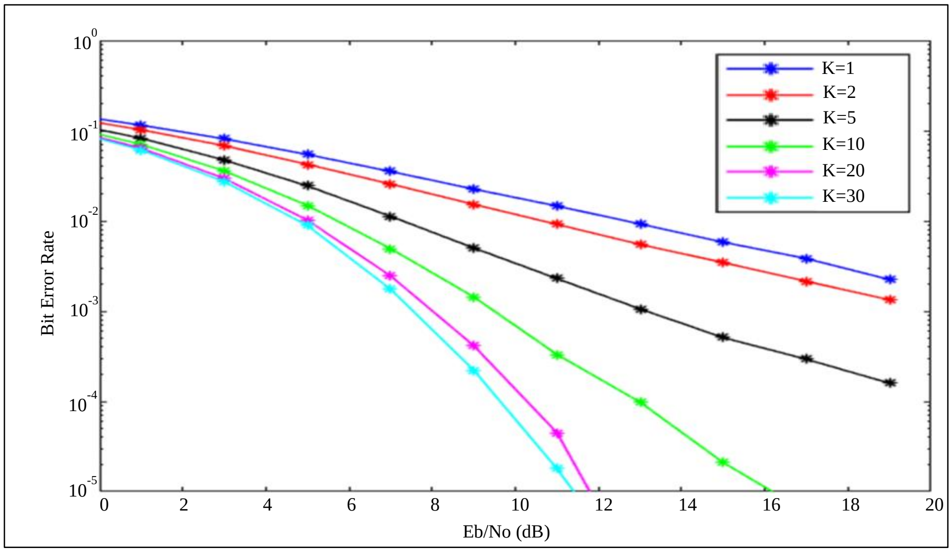

Fig. 16 BER performance of NR-DCSK in Racian fading channel with varying K-factor

Table 2. BER performance NR-DCSK scheme versus the SNR for different values of Racian factor K

K-Factor	SNR at BER of 10^{-2} (dB)
K = 1	13dB
K= 2	11dB
K = 5	8dB
K = 10	6dB
K = 20	5dB
K = 30	4dB

5. Conclusion

This study explored the efficacy of various chaotic communication schemes by employing a novel 2-D discrete chaotic system as the carrier signal. Visual confirmation of successful information retrieval at the receiver is provided in Figures 7, 10, and 13.

Further performance analysis focused on noise tolerance and BER under multipath fading channel conditions. Notably, NR-DCSK demonstrated superior performance compared to other chaos-based modulation techniques. Among the studied channels, Racian channels emerged as preferable for wireless applications. The investigation also revealed a crucial relationship between BER and SNR.

Overall, this paper contributes to a deeper understanding of research advancements in nonlinear chaos-based communication systems. These findings pave the way for future research endeavours, ultimately aiming to design enhanced chaos-based wireless communication systems.

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