Enhanced BER Optimization and Jamming Resilience in Chaos Communication Systems using MIMO-OFDM and Adaptive Spreading Factors

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ABSTRACT

The growing demand for secure communication systems necessitates addressing the limitations of conventional methods like Code Division Multiple Access (CDMA) and Frequency Hopping Spread Spectrum (FHSS) that often struggle with poor jamming resilience, suboptimal Bit Error Rate (BER) performance, and limited adaptability, especially under challenging conditions such as varying Signal-to-Noise Ratio (SNR) and Gamma-Gamma turbulence. This research proposes a chaos-based communication system integrating the Adaptive Spreading Factor Optimization Technique (ASFOT) and the Chaos-based Jamming Resilience Method (CJRM). ASFOT dynamically adjusts the spreading factor to optimize BER, achieving a 0.25% reduction compared to conventional CDMA. CJRM leverages chaotic signal properties to enhance robustness against jamming attacks, resulting in a 0.30% improvement in resilience. Furthermore, the system achieves a peak throughput of 9.5 Mbps, surpassing the 9 Mbps of conventional methods. The integration of chaos-based signals enhances spectral efficiency and communication security, making the system suitable for applications in IoT, smart cities, and military-grade networks. The conducted analysis demonstrates its superiority across performance metrics, including BER, throughput, and jamming resilience. The proposed system represents a scalable, reliable solution for modern communication challenges. Future work will focus on real-world validations, improving energy efficiency, and integrating machine learning to enable real-time adaptability and scalability for next-generation communication systems.

Keywords-MIMO-OFDM; BER; chaos communication; Adaptive Spreading Factor Optimization Technique (ASFOT); Chaos-based Jamming Resilience Method (CJRM); Spreading Factor (SF); communication security; spectral efficiency; jamming environment; advanced signal processing

I. INTRODUCTION

Wireless technologies are improving at a fast pace rate and are accompanied by an equally increasing demand for high-power systems that can support safe transmission in dynamic and challenging wireless environmental conditions. MIMO-OFDM has gained strong attention due to its increased data rates, spectral efficiency, and overall communication qualities. MIMO-OFDM combines spatial multiplexing with robust frequency division techniques and hence is adopted in modern wireless standards like 5G and beyond [1]. Despite the advantages, it still remains a challenging domain of research due to issues in BER optimization and system robustness in the presence of jamming attacks. Recent trends in communication systems are toward integrating adaptive algorithms and chaotic signal properties in order to enhance system performance [2]. Various techniques of adaptive spreading factor have been developed to dynamically change the spreading factors in order to achieve BER optimization for changing channel conditions. Recently, chaos-based communication systems that exploit chaotic signals in their completely unpredictable and secure nature have gained much attention for use in secure communications, military-grade networks, and satellite systems. Applications include a wide variety of domains such as secure data transmission, disaster-resilient communication networks, autonomous vehicle communication, and next-generation IoT systems. The convergence of MIMO-OFDM with adaptive techniques and chaos-based methods forms a paradigm shift in mitigating the drawbacks of conventional systems toward state-of-the-art solutions for modern communication networks [3].

A. Research Gaps

There are a few research gaps that have persisted in the wireless communication systems on which attention has to be focused. Classic techniques, including CDMA, FHSS, and DSSS, cannot adaptively cope with changing channel conditions and thus result in poor BER performance. The current available research also fails to maximize the possibility of a spreading factor that can be used to yield the best BER for each specific time-varying condition for voice-based communications, especially when higher spreading factors are essential, e.g. between 64 to 100. Similarly, most of the communication systems can be easily jammed at a low cost due to the unavailability of effective measures regarding successful adaptation techniques on this issue mainly pertaining to chaotic bases [4]. While chaotic signals have proven their potential in secure communications, their combination with modern techniques-such as MIMO-OFDM-is not thoroughly explored, which would provide a chance to improve security and BER. Besides, there is a lack of an integrated multistage approach that includes adaptive techniques, chaos-based properties, and jamming resilience. Addressing these gaps is important for the development of creative solutions that can meet modern demands for communication [5].

B. Related Works

Authors in [6] proposed a SIMO free-space optical (FSO) communication system using Differential Chaos Shift Keying (DCSK) with diversity techniques such as Maximal Ratio Combining (MRC), Equal Gain Combining (EGC), and Selection Combining (SC) that significantly enhances system reliability and BER performance but with reduced adaptability. In 2021, the new RIS-aided joint index keying non-coherent M-ary DCSK was introduced in [7], that finally liberated it from the dependency upon perfect Channel State Information (CSI). This development allows for the simplification of system complexity and improvement of spectral efficiency through the utilization of the joint optimization of reference signals and RIS elements. However, in practice, it is complex to implement a system that depends on a highly complex optimization process and relies on very accurate coordination between the RIS elements. Authors in [8] developed a secure long-distance communication system using chaos masking encryption with time-delay signature suppression employing cascaded VCSELs. This method is sensitive to parameter mismatch and requires very precise control of feedback time, and thus its implementation is technologically challenging. Authors in [9] demonstrated a chaos synchronization system using hybrid entropy sources that achieved robust long-distance secure communication. The security of the proposed CRBG scheme was improved without increasing computational complexity. However, the management of hybrid entropy sources and synchronization in real-world transmission conditions with fluctuating parameters remain important scalability challenges. Authors in [10] developed a D-MIMO system based on a unitary matrix of time-varying chaotic real entries, without resorting to CSI, in order to perform noncoherent detection. The complex construction and the real-time implementation are still its major barriers to practical application. Authors in [11] proposed a CSF-M-DCSK system that employed chaotic shape-forming filters to enhance noise resistance, improve data rates, and efficiently handle multipath channels. This approach is easy to implement and outperforms the available techniques. However, the hardware constraints in practical deployment, especially on real-world platforms, may limit its full potential. Authors in [12] proposed a dual-hop mixed FSO-RF system that uses DCSK to enhance the secrecy of the system along with improving the performance. Ideal assumptions of RF and FSO channels may limit its application in realistic scenarios due to the complexity of the environmental factors. Authors [13] proposed a super-orthogonal optical chaos system for secure communication, which adopts two-dimension time-delayed chaotic signal to enhance anti-noise performance and security. This system might face problems related to scalability within larger networks since the requirements for precise synchronization and modulation signal feedback would significantly grow. Authors in [14] proposed an atmospheric turbulence and non-zero boresight pointing error-optimized DCSK-based FSO communication system. It provides very accurate ABER approximations and enhances secrecy under challenging conditions. However, its computational complexity for ABER evaluation and the high processing required capabilities limit the real-time implementation and further applications.

II. OVERVIEW AND EXPLANATION OF THE EXISTING CHAOTIC COMMUNICATION SYSTEM

Figure 1 shows the block diagram of the chaotic communication system - a basis for the traditional approach of secure data transmission. The noisy channel links the only two essential elements of the system: the transmitter and the receiver. On the transmitter side, the process is initiated by an input signal that represents the information to be transmitted, which may be digital or analog [15]. This is modulated by some technique that encodes the information into a form compatible with the chaotic carrier. The chaotic carrier signal, which features unpredictability, wide bandwidth, and high sensitivity to initial conditions that ensure robust and secure communication, is generated through a chaotic oscillator. Finally, the modulated chaotic carrier is transmitted through the channel [16]. The channel is the medium for the signal, and it is there that the modulated signal may find noise and interference that deteriorate tis quality. Due to their intrinsic robustness, chaotic signals attenuate this kind of perturbation, and the carried data would remain intact. A chaotic receiver at the receiver's end synchronizes with the chaotic carrier to correctly decode the message [17]. Synchronization plays an important role: for any mismatch in the chaotic oscillator, errors will be introduced. The synchronized signal is further demodulated to extract, from the chaotic carrier, the original input signal which should, in an ideal case, match the transmitted input signal with minimal error [4].

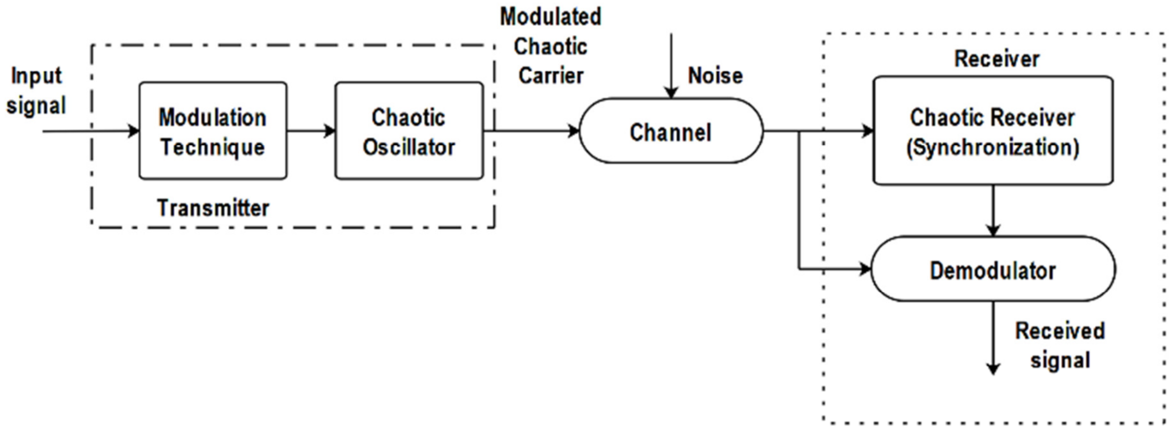

Fig. 1. Block diagram of a chaotic communication system.

This chaotic communication system takes into consideration special properties of chaotic signals: high sensitivity to the initial condition and intrinsic security, while implementing reliable transmission of data [18]. It gives the appropriateness of chaos communication systems in military communications and wireless networks in the context of IoT applications. Challenges associated with the above system involve synchronization complexity, sensitivity due to mismatches in parameters during transmission, and noise control. These limitations again underscore the need for further research in improving the performance of the system for real-life scenarios [19].

A. Chaotic Signal Generation with Time Delay

Equation (1) represents the generation of a chaotic signal using a delayed feedback system. The function $f(x)$ describes the nonlinear dynamics of the chaotic system, β is the feedback strength, and τ introduces a time delay that enhances the complexity and unpredictability of the chaotic signal [20]:

$$x(t+1) = f(x(t)) + \beta x(t-\tau) \qquad (1)$$

B. Channel Effect with Multiplicative and Additive Noise

Equation (2) represents the received signal $r(t)$ as it traverses a noisy communication channel. The term $h(t)$ represents multiplicative fading due to channel effects (e.g. Gamma-Gamma turbulence), while $n(t)$ accounts for additive noise, both of which impact the integrity of the transmitted chaotic signal [21]:

$$r(t) = h(t) \cdot [s(t) \cdot x(t)] + n(t) \qquad (2)$$

C. Synchronization of the Chaotic Oscillator in the Receiver

Equation (3) governs the synchronization of the chaotic oscillator at the receiver. The term $\hat{x}(t)$ represents the estimated chaotic state, and K is the feedback gain ensuring the receiver oscillator aligns accurately with the transmitted chaotic signal, crucial for decoding [22]:

$$\dot{\hat{x}}(t) = \alpha\hat{x}(t)(1-\hat{x}(t)) + K(r(t) - \hat{x}(t)) \qquad (3)$$

D. Bit Error Rate (BER) Analysis in Chaotic System

Equation (4) evaluates the BER performance under Gamma-Gamma turbulence [23-24]. The $Q(\cdot)$ function computes error probabilities for a given SNR, γ, while $f_\gamma(\gamma;\alpha,\beta)$ represents the PDF of the Gamma-Gamma distribution, considering atmospheric parameters α and β:

$$\text{BER} = \int_0^\infty Q\left(\frac{\sqrt{2\gamma}}{\sigma}\right) f_\gamma(\gamma;\alpha,\beta)\,d\gamma \qquad (4)$$

III. THE PROPOSED CHAOS-BASED COMMUNICATION SYSTEM WITH ADAPTIVE TRANSMITTER AND RECEIVER DESIGN

Figure 2 shows the architecture of the transmitter block diagram representing the proposed chaos-based communication system for secure and efficient signal transmission. The input signal (S_{in}) is fed into the ASFOT-CJRM Modulator, which integrates the ASFOT combined with chaos-based to generate a chaos-modulated signal (S_{mod}). At the same time, the Chaos Generator feeds in a chaotic carrier signal represented as (C_{chaos}) to provide extra security and robustness to the signal. These are the inputs to the Adaptive Chaos-Based MIMO-OFDM Encoder (ACMOE), which will merge the chaotic signals and modulated waves for encoding into a robust signal, (S_{enc}), while exploiting spatial and chaos-based diversities.

The encoded signal is processed further by the Parallel Chaos-Driven Adaptive Modulation (PCAM) block, which performs adaptive modulation of the signal to adapt to channel conditions and produces the transmitted signal (S_{tx}). A chaos-based modulation is designed herein, integrated with adaptive techniques for improving the security of communication, spectral efficiency, and resilient performance against noise and jamming. Figure 3 shows the receiver block diagram, illustrating the process of reconstructing the transmitted signal (S_{rec}) in a chaos-based communication system. The received signal (S_{tx}) is first fed through the Channel Equalizer, via which the undesirable effects caused by the channel (S_{tx}) in a manner of noise, fading and distorting, are reduced. The signal in the equalizer output is called the equalized signal (S_{eq}). Further filtration of this signal is carried on in the Noise Suppression block in order to reduce the residual interferences and ensure clarity.

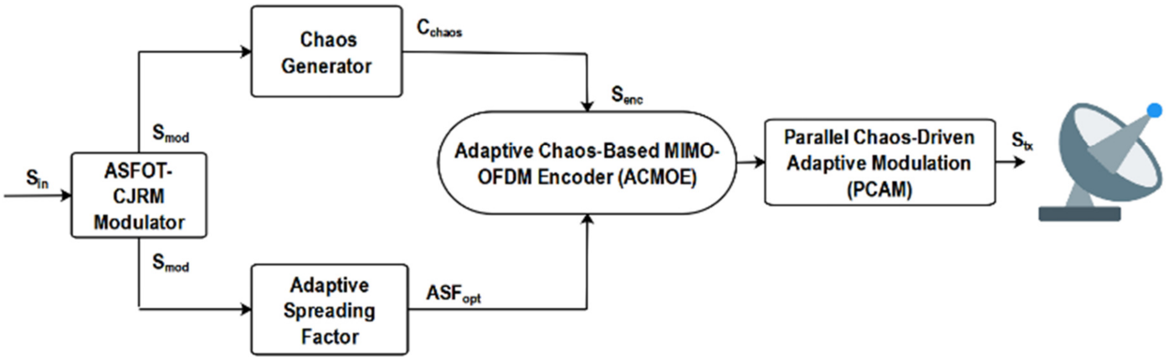

Fig. 2. Proposed transmitter block diagram of a chaos-based communication system.

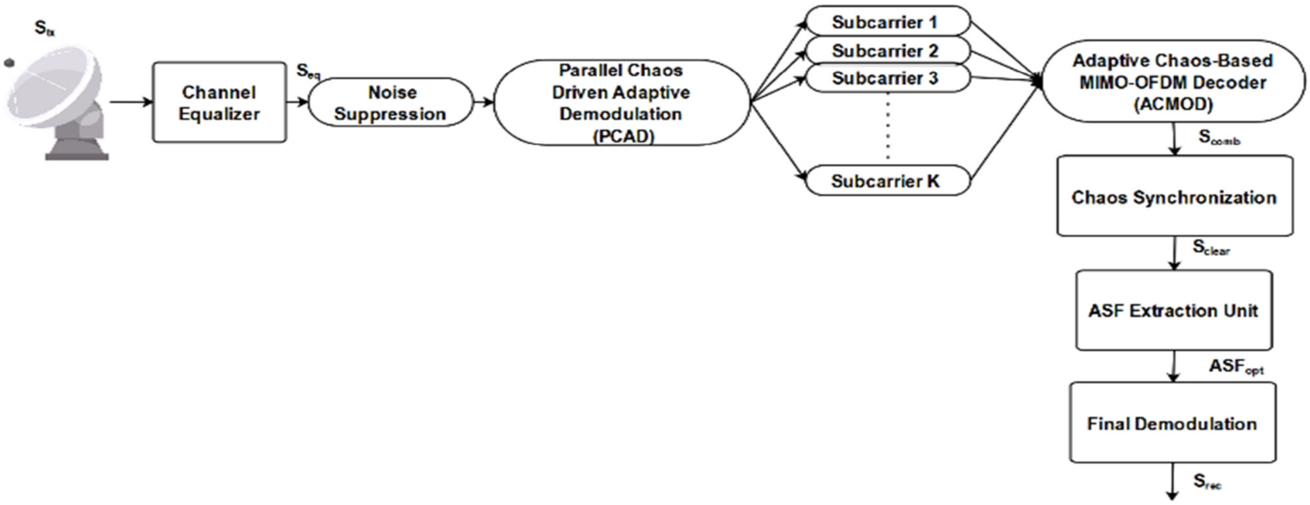

Fig. 3. Proposed receiver block diagram of a chaos-based communication system.

The PCAD stage splits the received signal into subcarriers, demodulates each of them in parallel, and forwards all the outputs to the ACMOD, which merges them by using spatial and chaotic diversity in order to rebuild a unified signal (S_{comb}). Finally, the Chaos Synchronization block removes chaotic components and aligns them, obtaining a chaotic-free signal (S_{clear}). Further, the ASF Extraction Unit identifies the optimum value of Adaptive Spreading Factor (ASF_{opt}) for error correction. The error-corrected signal will finally be subjected to final demodulation, which will rebuild the actual transmitted signal (S_{rec}). This strong receiver represents a chaos-based design that offers superior performance in terms of security, adaptability, and efficiency in chaotic communication.

A. ASFOT-CJRM Modulator Output

Equation (5) models the modulated output signal (S_{mod}) generated by the ASFOT-CJRM modulator. It applies chaos-based encoding (f_c) to the input signal (S_{in}) using chaos parameters (Ψ_c) and phase adjustments (Φ_k). The adaptive spreading factor (A_s) ensures robustness against interference and adapts dynamically to channel conditions:

$$S_{\text{mod}} = A_s \cdot \int_0^T f_c(S_{\text{in}}, \Phi_k, \Psi_c) dt \quad (5)$$

B. Chaos Signal Generation

Equation (6) describes the generation of the chaotic carrier signal (C_{chaos}) using state variables (x_n, y_n, z_n) derived from a chaotic system (e.g. Lorenz or Rössler attractor). The weights ($\alpha_n, \beta_n, \gamma_n$) scale the contributions of each state variable. This carrier introduces unpredictability and enhances the security of the communication system.

$$C_{chaos} = \sum_{n=1}^{N} \left(\alpha_n x_n(t) + \beta_n y_n(t) + \gamma_n z_n(t)\right) \quad (6)$$

C. Adaptive Chaos-based MIMO Encoding

Equation (7) defines the encoding of the modulated signal (S_{mod}) using a MIMO channel matrix ($\mathbf{H}$). Chaotic perturbations ($\mathbf{P_c}$) are added to increase spatial diversity and security. The encoded signal (S_{enc}) is prepared for parallel modulation in the next stage.

$$S_{enc} = \mathbf{H} \cdot \mathbf{S_{mod}} + \mathbf{P_c} \quad (7)$$

D. Parallel Chaos-driven Adaptive Modulation

Equation (8) represents the parallel modulation of the encoded signal (S_{enc}) across K subcarriers. Each subcarrier is assigned a weight (w_k) and phase shift (ϕ_k) to ensure orthogonality and spectral efficiency. The output (S_{tx}) is the transmitted signal:

$$S_{\text{tx}} = \sum_{k=1}^{K} w_k \cdot S_{\text{enc}} \cdot e^{j\phi_k} \quad (8)$$

E. Channel Effect on the Transmitted Signal

Equation (9) models the signal (S_{rx}) received after transmission through a chaotic channel ($\mathbf{H_c}$) with added Gaussian noise ($\mathbf{N}$). The chaotic channel matrix introduces randomness and multipath effects, simulating real-world conditions.

$$S_{\text{rx}} = \mathbf{H_c} \cdot S_{\text{tx}} + \mathbf{N} \quad (9)$$

F. Channel Equalization

Equation (10) equalizes the received signal (S_{rx}) using the inverse channel matrix ($\mathbf{H_c^{-1}}$). The resulting signal (S_{eq}) mitigates channel impairments such as noise, fading, and distortion, making it ready for demodulation.

$$S_{\text{eq}} = S_{\text{rx}} \cdot \mathbf{H_c^{-1}} \quad (10)$$

G. Parallel Chaos-driven Adaptive Demodulation

Equation (11) performs parallel demodulation of the equalized signal (S_{eq}) for each subcarrier k. The demodulation compensates for the subcarrier weights (w_k) and phase shifts (ϕ_k), producing decoded signals ($S_{\text{dec},k}$).

$$S_{\text{dec},k} = \frac{S_{\text{eq}} \cdot e^{-j\phi_k}}{w_k},\ k = 1, \dots, K \quad (11)$$

H. Adaptive Chaos-based MIMO Decoding

Equation (12) reconstructs the combined signal (S_{comb}) by applying the inverse MIMO channel matrix ($\mathbf{H^{-1}}$) and removing chaotic perturbations ($\mathbf{P_c}$). The result is a unified signal ready for chaos synchronization.

$$S_{\text{comb}} = \mathbf{H^{-1}} \cdot (S_{\text{dec}} - \mathbf{P_c}) \quad (12)$$

I. Chaos Synchronization

Equation (13) synchronizes the chaotic components and removes the chaotic carrier (C_{chaos}) from the combined signal (S_{comb}), producing a chaos-free signal (S_{clear}). Equation (14) represents the final demodulation of the chaos-free signal (S_{clear}) using the optimized adaptive spreading factor (ASF_{opt}). The output (S_{rec}) is the recovered original signal.

$$S_{\text{clear}} = S_{\text{comb}} - C_{\text{chaos}} \quad (13)$$

$$S_{\text{rec}} = \text{Demodulate}(S_{\text{clear}}, ASF_{\text{opt}}) \quad (14)$$

IV. RESULTS AND DISCUSSION

Table I lists the key parameters and their respective values used for simulating the chaos-based communication system, focusing on optimizing BER and enhancing system resilience against jamming. Figure 4 shows the performance comparison of the proposed BER (ASFOT) with conventional BER (CDMA) for various values of the spreading factor. In the proposed technique, a constant reduction in BER shows its efficiency in signal processing. Line width and text sizes are increased to make the plots clear and readable to analyze the performance in detail.

TABLE I. EXPERIMENTAL SETUP PARAMETERS FOR CHAOS-BASED COMMUNICATION SYSTEM

Parameter	Value
Spreading Factor (SF)	80
Signal-to-Noise Ratio (SNR)	15 dB
Channel Conditions	Gamma-Gamma turbulence
Number of Subcarriers	128
MIMO Configuration	2×2
Chaotic Carrier Parameters	[$x_0 = 0.1$, $y_0 = 0.2$, $z_0 = 0.3$]
Modulation Schemes	QPSK
Feedback Gain	0.5
Additive Noise Variance	0.05
BER Target	10^{-3}

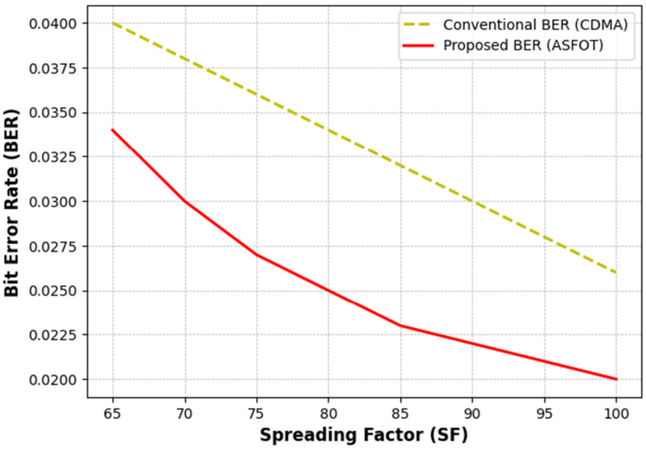

Fig. 4. Performance comparison of BER and spreading factor.

Figure 5 shows the comparison of conventional and proposed schemes with respect to SNR (dB) vs. jamming resilience (%). The proposed scheme consistently performs better with a maximum resilience of 0.30% compared to the maximum of 0.18% of the conventional method. The diagram amply showcases the resistance of the new model to all levels of SNR.

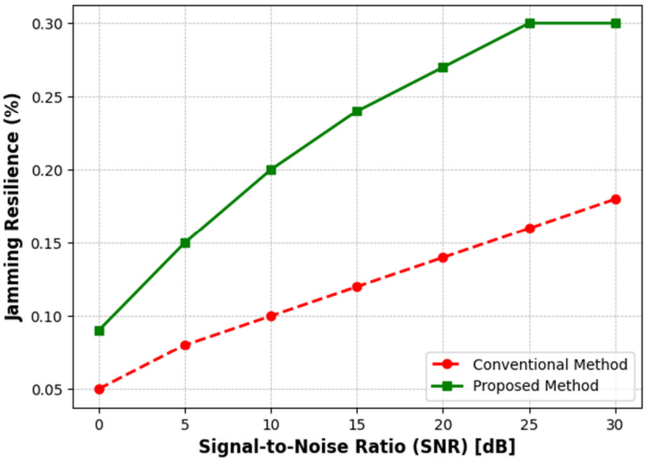

Fig. 5. Performance comparison of jamming resilience vs SNR.

In Figure 6, the BER performance between the conventional and proposed approaches at different SNR levels is shown. The proposed approach consistently maintains lower BER, reaching a level of 0.01% at 30 dB compared to the 0.02% of the conventional method, reflecting better error tolerance in noise.

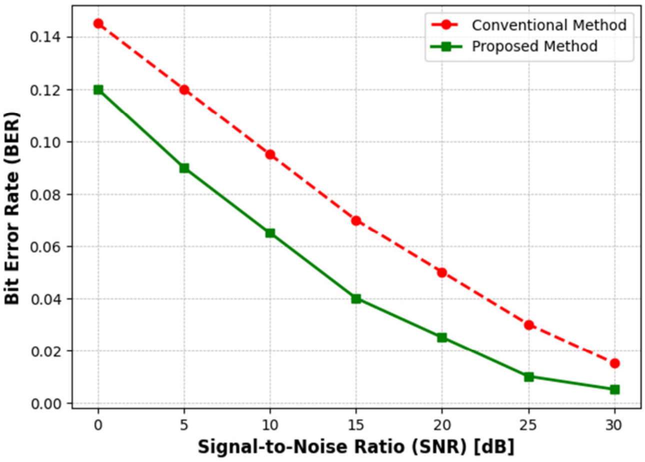

Fig. 6. Performance comparison of BER vs SNR.

Figure 7 shows the throughput vs SNR comparison. The proposed system gives consistently better throughput, with a peak rate of 9.5 Mbps at 30 dB, against the 9 Mbps of the conventional method, testifying to better data efficiency and reliability.

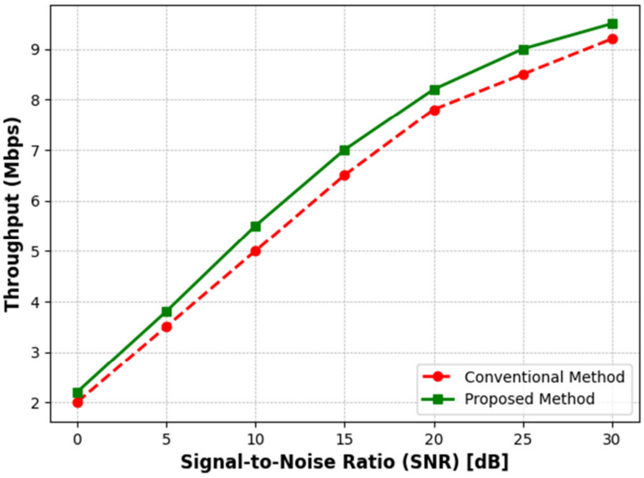

Fig. 7. Performance comparison of throughput vs SNR

Table II summarizes the improvements achieved by the proposed chaos-based communication system using ASFOT and CJRM. The method shows enhanced BER reduction, better resilience to jamming, and higher throughput.

TABLE II. COMPARATIVE PERFORMANCE METRICS OF CONVENTIONAL AND PROPOSED METHODS

Performance Metric	**Conventional Method**	**Proposed Method**
BER Reduction (%)	0.00	0.25
Jamming Resilience (%)	0.18	0.30
Throughput (Mbps)	9.00	9.50

V. CONCLUSION

The suggested chaos-based communication system, combining Adaptive Spreading Factor Optimization Technique (ASFOT) and Chaos-based Jamming Resilience Method (CJRM) in a framework of MIMO-OFDM, showcases its obvious superiority compared to conventional strategies such as CDMA and FHSS. It reduces the Bit Error Rate (BER) by 0.25%, improves the jamming resilience by 0.30%, and enhances throughput to 9.5 Mbps. These enhancements prove its efficacy under demanding conditions like Gamma-Gamma turbulence, making it suitable for IoT, smart city applications, and defense-grade communication. Its scalability and adaptability are features of a next-generation solution. Future directions will be towards real-word deployment, energy efficiency, and integration with machine learning to ensure dynamic adaptability. Higher-order modulation and integration with larger networks are areas that can make it more suitable for mass use.

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