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RESEARCH ARTICLE

Detection of Weak Signals Under Low SNR Stochastic Resonance System

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ABSTRACT To solve the problem that weak signals are difficult to detect accurately in low signal-to-noise ratios, this paper presents a method to achieve effective detection of weak signals, applying the method of stochastic resonance to bistable systems. The principle of the method is that by transferring part of the noise energy to the signal energy, enabling the detection of weak signals at low signal-to-noise ratios. It makes it easier to extract the signal at the receiving end. This model designs a parametrized conditioning system based on the factors influencing the output power spectrum and output SNR of a stochastic resonant system. Based on the experimental results, the influence of parameters a and b on the model can be analysed, and the optimal noise intensity range of the system can be found. At the receiving end of the system, the constellation diagram and BER are used as a measure of system performance. Simulation experiments show that stochastic resonance can effectively enhance the energy of weak signals under low signal-to-noise conditions, and the demodulation performance of the system is significantly better than that of the system without the use of stochastic resonance.

INDEX TERMS Stochastic resonance in trap, weak OFDM signal, signal enhancement, output SNR, parameter adjustment.

I. INTRODUCTION

With the rapid increase in the number of wireless communication devices and the growing number of various types of electromagnetic signals, the background noise interference in the communication system is significantly enhanced. As a result, the signal is often characterized by a low SNR when it reaches the receiver in the presence of interference. Conventional signal detection methods mostly suppress or filter the noise to facilitate detection of weak signals, but they are suitable for systems with high output SNR. When the background noise is too strong, weak signals cannot be effectively detected. In this regard, the stochastic resonance method that enhances the SNR by utilizing noise is widely valued.

The stochastic resonance method allows the presence of noise, and through the resonant effect of noise and signal, i.e., stochastic resonance, part of the noise energy will be superimposed on the signal to be detected, thus making the signal amplified and enhanced for easy extraction at the receiving end, and the output SNR is improved to achieve accurate detection of the expected signal. Stochastic resonance as a new method to enhance weak signals, how noise affects the system has attracted the attention of researchers in various subject areas. Goswami et al. [1] studied the relaxation problem under nonequilibrium constraints, Hohenegger et al. [2] discovered the average first-pass time as a function of particle radius. In communication signal processing, Peng Hao et al. [3] proposed a fractional-order coupled system under three-state excitation for depicting the motion of coupled particles with mass rise and fall in an elastic medium and gave a response explanation for the system amplitude gain. Hasegawa [4] analyzed the effect of memory effect on the system in different situations by studying the system power spectrum amplification factor. Lifang et al. [5] proposed a segmented nonlinear system model that can effectively extract the characteristic frequency with good amplification capability and applied it to bearing fault detection. Jianjun [6] proposed a traveling wave noise reduction method

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to solve the problem that traveling wave signals are not easily and effectively extracted, which can effectively and accurately extract traveling wave signals. Jiang et al. [7] studied multiplicative square wave signals and multiplicative double-valued noise, regarding their performance in stochastic resonant systems, and did a related study. Gang [8] studied the effect of coupling coefficients and asymmetric coefficients on the power spectrum gain factor based on a two-dimensional four-stable potential system and proved that its detection performance is better than that of a one-dimensional three-dimensional potential system. In a study of a second-order underdamped periodic system, Saikia [9] found the stochastic resonance phenomenon that appeared in the high-frequency part of the excitation signal, and the damping parameters and signal amplitude of the system limit the stochastic resonance phenomena.

On the other hand, the multi-stable periodic potential model has been widely used in biological and engineering fields as well [10], [11], and the study of noise-induced dynamics in the periodic potential model has been equally fruitful. In asymmetric tristable systems, coherent resonances are suppressed by memory time and stochastic resonances are enhanced instead [12]. Reenbohn [13] found that underdamped particles can exhibit stochastic resonance and ratcheting effect at low temperature, while Yanfei et al. [14] studied the stochastic multiple resonance phenomenon by analyzing the differential equations of multiplicative dichotomous noise and additive white noise.

In this paper, by creating a stochastic resonance system model under low SNR conditions, we first analyze the stochastic resonance phenomenon, and then design a parameter adjustment model for the influence factors affecting the system output and the variation of the system output SNR. And using the weak OFDM (Orthogonal Frequency Division Multiplexing) signal as the input signal, combined with the theory of stochastic resonance, the effect of stochastic resonance on the anti-noise performance of the system is studied. By adjusting each influence factor, the output BER of the system is reduced. The experimental results show that the stochastic resonance can effectively improve the anti-noise performance of OFDM system and reduce the demodulation BER under the low SNR condition.

II. BISTABLE STOCHASTIC RESONANCE SYSTEM

A. SYSTEM EQUATIONS

The stochastic resonance system is shown in Figure 1, and its components include three: the input signal, noise, and nonlinear bistable system. Through the joint action of these three components, some noise energy is superimposed on the signal energy, which increases the energy of the signal to be detected. The useful signal is generally a weak signal denoted by $s(t)$, the background noise is selected as Gaussian noise denoted by $n(t)$, and the nonlinear system is selected as a typical bistable system.

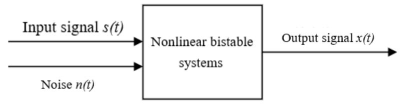

FIGURE 1. **SR Model of Bistable System.**

The bistable system is a typical nonlinear system. The nonlinear Langevin equation of the system under the joint action of the input useful signal $s(t)$ and the Gaussian white noise $n(t)$ is as follows:

$$x'(t) = -U'(x) + s(t) + n(t) \tag{1}$$

$U(x)$ is the system potential function, and a and b are the system parameters. Then the standard expression for the quadratic potential function is as follows:

$$U(x) = -\frac{1}{2}ax^2 + \frac{1}{4}bx^4 \tag{2}$$

The intensity of Gaussian white noise is D. The steady-state point of the bistable system is $x_{\pm} = \pm\sqrt{a/b}$, and the height of the potential barrier is $\Delta U = a^2/4b$. Taking the system parameters as $a = b = 1$ when there is no input signal and noise, the potential function curve is shown in Figure 2.

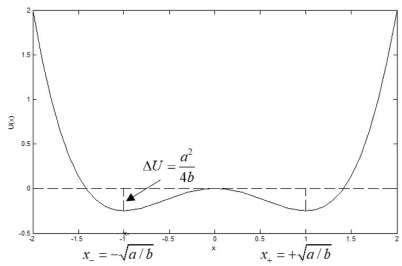

FIGURE 2. **Bistable system potential function curve.**

When $s(t)$ is a periodic sinusoidal signal $A\cos(2\pi f_0 t)$, the system equation is as follows:

$$x'(t) = ax - bx^3 + A\cos(2\pi f_s t) + n(t) \tag{3}$$

The commonly used algorithm for solving the differential equation is the Runge-Kutta algorithm, and the fourth-order Runge-Kutta algorithm with good accuracy is used here for solving Eq. (3). Let the sampling frequency be f, then the time step is $h = 1/f$. The right-hand part of Eq. (3) is denoted by $f(t, x)$, where x and t are the output signal values of the stochastic resonant system at the n-th and $(n+1)$-th moments, and k_1, k_2, k_3 and k_4 are the iteration parameters.

$$\begin{cases} x_{n+1} = x_n + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4) \\ k_1 = f(t_n, x_n) \\ k_2 = f\left(t_n + \frac{h}{2}, x_n + \frac{h}{2}k_1\right) \\ k_3 = f\left(t_n + \frac{h}{2}, x_n + \frac{h}{2}k_2\right) \\ k_4 = f(t_n + h, x_n + hk_3) \end{cases} \tag{4}$$

While the system has no input signal excitation and only noise is present,the particles will move repeatedly within the left and right potential wells of the system and the average crossing rate (Kramers rate) of the system is expressed as:

$$r_K = \frac{a}{\sqrt{2}\pi} \exp\left(-\frac{\Delta U}{D}\right) \tag{5}$$

The response of a bistable system is divided into the following three cases:

a)With the input signal $A = 0$ and noise $n(t) = 0$, $x(t)$ will fall into a certain potential well as $t \to \infty$. The system output is $x(t) = 0$ with the initial value of $x_0 = 0$.

b)While the input signal $A = 0$ and the noise $n(t) \neq 0$, the system undergoes a leap transformation between the two potential wells, with the leap rate determined by γ_K. The rate depends on both the distribution and intensity of the noise.

c)When the input signal $A \neq 0$ and the noise $n(t) \neq 0$, if the input signal amplitude is $A < A_{\max}$ (the critical value of the system output: $A_{\max} = \sqrt{4a^3/27b}$), the input signal energy is too small and cannot provide enough energy for the particle to support the leap. As a result, the particle can only land in one of the potential wells. On the other hand, when the input signal amplitude is $A > A_{\max}$, the energy of the particle is sufficient to support it in crossing the potential barrier, thereby completing the periodic transition between the left and right potential wells.

In a stochastic resonance system, the assistance of noise energy enables the particle to gain energy from the noise, even when $A < A_{\max}$, thus enabling it to cross the potential barrier. This is the principle behind the phenomenon of stochastic resonance for the detection of weak signals.

B. PROPERTIES OF STOCHASTIC RESONANCE

In order to analyze the characteristics of stochastic resonance, particularly the frequency characteristics, the phenomenon can be described using the power spectral density function. When the system is not excited by an external signal, the jump rate between the two steady states is constant. When the system is excited by an external periodic signal, the leap rate between the two potential wells is also periodic because of the periodic nature of the signal. The probability, denoted by $p_\pm(t)$, is the probability that the system is located at the left and right steady-state points at moment t, which is represented by $x_\pm(t)$, that is, $p_\pm(t) = P(x(t) = x_\pm)$. In the adiabatic approximation, the equilibrium time within a potential well is almost instantaneous, and the time consumed is much less than the equilibrium time between potential wells. Therefore, the local equilibrium time is considered to be instantaneous, and the time consumed is negligible, and only the time consumed by the leap between the left and right potential wells is considered.

At this point, we can write the equation for the system under the excitation of a periodic external signal as follows:

$$p'_+(t) = -p'_-(t) = -r_+(t)p_+(t) + r_-(t)p_-(t) \tag{6}$$

Of these $p_+(t) + p_-(t) = 1$.

Solving the differential equation yields:

$$p_+(t) = h^{-1}(t)\left[p_+(t_0)\,h(t_0) + \int_{t_0}^{t} r_-(s)h(s)ds\right] \tag{7}$$

Of these $h(t) = \exp\left\{\int_{t_0}^{t}[r_+(s) + r_-(s)]\,ds\right\}$,$p_\pm(t_0)$ denotes the initial probability at moment t_0. Let $r_\pm(t) = g\left[\alpha + \beta_s \cos(f_s t)\right]$, $\beta = \beta_s \cos(f_s t)$.

By performing a Taylor expansion of $r(t)$, we obtain:

$$r_\pm(t) = \frac{1}{2}\left[K_0 \mp K_1\beta_s \cos(f_s t) + K_2\beta_s^2 \cos^2(f_s t) \mp \ldots\right] \tag{8}$$

Of these $K_0 = 2g(\alpha)$, $K_n = 2\frac{(-1)^n d^n g(\alpha)}{n! d\beta^n}$

By substituting equation (8) into equation (7), we obtain the probability solution of the output signal at the steady state point:

$$\begin{aligned} p_+(t \mid x_0, t_0) = \frac{1}{2}\Big\{&\exp[-k_0(t-t_0)]\Big[\delta_{x_{oc}} \\ &-1 - \frac{k_1\beta_s \cos(f_s t_0 - \varphi)}{\sqrt{k_0^2 + f_s^2}}\Big] \\ &+1 + \frac{k_1\beta_s \cos(f_s t - \varphi)}{\sqrt{k_0^2 + f_s^2}}\Big\} \end{aligned} \tag{9}$$

Of these $\varphi = \tan^{-1}(f_s/\mathrm{k}_0)$, $p_+(t \mid x_0, t_0)$ represents the probability that a particle located at x_0 at moment t_0 will move to the right steady state x_+ at moment t. $\delta_{x_{0c}}$ is the Kronecker function:

$$\delta_{x_{0c}} = \begin{cases} 0 & \text{Particle falls into the left steady state point} \\ 1 & \text{Particle falls into the right steady state point} \end{cases}$$

The autocorrelation function of the system output is obtained according to Equation (9):

$$\begin{aligned} &\langle x(t)x(t+\tau) \mid x_0, t_0\rangle \\ &\quad = \frac{a}{b}\{[2p_+(t+\tau \mid x_+, t) - 1 \\ &\qquad +2p_+(t+\tau \mid x_-, t) - 1]\,p_+ \\ &\qquad \times (t \mid x_0, t_0) - [2p_+(t+\tau \mid x_-, t) - 1]\} \end{aligned} \tag{10}$$

When t_0 tends to infinity, the limit is taken for the autocorrelation function:

$$\begin{aligned} &\langle x(t)x(t+\tau)\rangle \\ &\quad = \lim_{t_0 \to -\infty} \langle x(t)x(t+\tau) \mid x_0, t_0\rangle \\ &\quad = \frac{a}{b}\exp[-k_0|\tau|]\left[1 - \frac{k_1^2\beta_s^2\cos^2(f_s - \varphi)}{k_0^2 + f_s^2}\right] \\ &\qquad + \frac{\alpha k_1^2\beta_s^2\{\cos(f_s\tau) + \cos[f_s(2t+\tau) + 2\varphi]\}}{2b\left(k_0^2 + f_s^2\right)} \end{aligned} \tag{11}$$

In practical measurements, the correlation function is based on statistical significance and is averaged over the correlation function obtained at different moments:

$$\langle x(t)x(t+\tau)\rangle = \frac{a}{b}\exp[-k_0|\tau|]\,[1$$

$$- \frac{k_1^2 \beta_s^2 \cos^2 (f_s - \varphi)}{k_0^2 + f_s^2} \Bigg] + \frac{\alpha k_1^2 \beta_s^2 \cos (f_s \tau)}{2b \left(k_0^2 + f_s^2\right)} \tag{12}$$

By the Wiener-Khinchin theorem, the Fourier transform of equation (12) is the average power spectral density of the system, which is

$$S(\omega) = \int_{-\infty}^{+\infty} \langle x(t)x(t+\tau)\rangle \exp(-j\omega\tau)dt = S_s(\omega) + S_n(\omega) \tag{13}$$

where: $S_s(\omega)$ is the signal power spectrum and $S_n(\omega)$ is the noise power spectrum.

$$S_s(\omega) = \left[1 - \frac{a^3 A^2 \gamma}{bD^2 \left(2a^2\gamma + \pi^2 f_s^2\right)}\right] \left[\frac{4\sqrt{2} a^2 A^2 \gamma}{\pi b \left(\frac{2a^2\gamma}{\pi^2} + \omega^2\right)}\right] \tag{14}$$

$$S_n(\omega) = \left[\frac{2a^4 A^2 \gamma}{\pi b^2 D^2 \left(\frac{2a^2\gamma}{\pi^2} + f_s^2\right)}\right] \delta(\omega - f_s) \tag{15}$$

where:$\gamma = exp(-2\delta/D)$, So the output signal to noise ratio of the system is:

$$SNR = \frac{\sqrt{2} a^2 A^2 \exp\left(-\frac{\Delta U}{D}\right)}{4bD^2 \left[1 - \frac{2a^2\gamma + \pi^2 f_S^2}{\pi^2}\right]} \tag{16}$$

When A is much less than 1, the output SNR satisfying the adiabatic approximation condition can be expressed as:

$$SNR \approx \frac{\sqrt{2} a^2 A^2 \exp\left(-\frac{\Delta U}{D}\right)}{4bD^2} \tag{17}$$

Some conclusions can be drawn from the output SNR.

(a) When the noise intensity D tends to 0, the denominator tends to 0 slower than the numerator tends to 0 and the SNR tends to 0.

(b)As the noise intensity D tends to infinity, the numerator tends to be constant, while the denominator tends to infinity and the SNR tends to 0.

Therefore, as the noise intensity gradually increases, the output SNR will exhibit a trend of first rising and then falling, as shown by the graph, which has an extreme value. This indicates that there exists an optimal noise intensity for the system to achieve the conditions for the occurrence of stochastic resonance.

III. DETECTION OF WEAK OFDM SIGNALS BASED ON STOCHASTIC RESONANCE

A. OFDM

The OFDM signal is a multi-carrier signal and the received OFDM signal can be expressed as:

$$s_{\text{in}}(t) = \text{Re}\left[\sum_{k=0}^{N-1} d_k \,\text{rect}\left(t - \frac{T_s}{2}\right) \exp(j2\pi f_k t)\right] = \sum_{k=0}^{N-1} [\alpha_k \cos(2\pi f_k t) - \beta_k \sin(2\pi f_k t)] \tag{18}$$

where N denotes the number of OFDM signal subcarriers, $d_k = \alpha_k + j\beta_k$ denotes the number of symbol mapping complexes on the subcarriers, $rect()$ is a rectangular function, Ts is a symbol period, and f_k denotes the frequency of the k-th subcarrier.

In today's communication systems, OFDM signals are widely used due to their excellent performance, and some of OFDM's characteristics are advantageous for the occurrence of stochastic resonance phenomenon.

(a)High frequency utilization: OFDM divides the spectrum and data on each subcarrier can be transmitted at different time intervals. This spectrum division technique helps to enhance stochastic resonance phenomenon, as multiple frequency components may exist in the random excitation signal.

(b)Strong controllability: OFDM technology can adjust the bandwidth and center frequency of the signal by adjusting the number and spacing of subcarriers, thereby achieving control over the signal. This controllability helps to study the resonance frequency and resonance width of stochastic resonance phenomenon.

(c)Strong anti-interference ability: OFDM technology uses frequency division multiplexing to divide the signal into multiple subcarriers, which can improve the system's anti-interference ability and reduce the impact of external interference on stochastic resonance experiments.

(d)Easy to process and analyze experimental results: OFDM signals have periodicity and orthogonality, so the signal can be transformed from time domain to frequency domain using FFT, which is convenient for processing and analyzing experimental results.

(e)Strong scalability: OFDM technology can be easily combined with other technologies, such as MIMO, CDMA, etc., to achieve deeper research on stochastic resonance phenomenon.

Due to these characteristics, OFDM signals are used as the input signal in this paper to study the restorative effect of stochastic resonance on weak signals.

B. BUILDING DETECTION MODELS

The OFDM signal stochastic resonance model is established using 16QAM modulation. At the transmitter, data is subjected to serial and parallel transformation, followed by IFFT and parallel-serial transformation, and the addition of cyclic prefixes. The resulting signal is transmitted through a Gaussian white noise channel and received at the receiver end, where stochastic resonance occurs. This results in the signal oscillating within the potential well, completing the transfer of noise energy to signal energy. At the receiver end, the system performs the inverse operations of those at the transmitter, i.e. de-cyclic prefix, FFT, and parallel-serial conversion, to demodulate the weak OFDM signal. The noise immunity of the system is measured by comparing the signal constellation diagrams before and after processing, and calculating the BER.

The specific steps are as follows:

Transmitter:

(a) Generation of a stochastic binary bit stream, 16QAM constellation mapping.

(b) Performing parallel-serial transformation, IFFT, and parallel-serial transformation again on the mapped data to obtain a modulated OFDM signal.

(b) Adding a cyclic prefix to the OFDM signal.

The system channel is a Gaussian white noise channel.

Receiver side:

(a) Obtain the mixed input signal $s(t) + n(t)$, $s(t)$ the weak OFDM signal to be detected and $n(t)$ the background noise.

(b) Performing stochastic resonance on the mixed input signal to solve the OFDM signal.

(c) removing the cyclic prefix and performing an FFT on the receiver signal.

(d) inverse mapping of the constellation diagram on the receive signal and series-parallel transformation to obtain the demodulated binary bit stream.

(e) The BER is used as a measure to quantify the detection performance of the system.

C. EFFECT OF SYSTEM PARAMETERS AND NOISE INTENSITY ON STOCHASTIC RESONANCE

This paper investigates the effect of different system structure parameters and noise intensity on the demodulation performance of bistatic stochastic resonant systems. To isolate the impact of individual variables, only one parameter is varied in each experiment, including the system potential function parameters a and b, the input signal amplitude A, and the noise intensity D, while keeping all other factors constant.

The Fokker-Planck equation for x is obtained from the probability density distribution function $\rho(x, t)$.

$$\frac{\partial\rho(x,t)}{\partial} = -U''(x)\frac{\partial}{\partial x}\left[(x - x_s)\,\rho(x,t)\right] + D\frac{\partial^2}{\partial^2}\rho(x,t) \tag{19}$$

The minimum non-zero eigenvalue of equation (19) is $\lambda_m = U''(x)$, and $\lambda_m = \lambda_m(bD, s(t)/\sqrt{D})$. As can be seen from equation (19), the stochastic resonance phenomenon is influenced by two factors: the system parameter b and the noise intensity D. Increasing both the system parameter b and the noise intensity D to a certain level can affect the system output, causing the system to exhibit stochastic resonance within the trap, and thus enhance the signal energy.

The effect of signal amplitude on stochastic resonance: the higher the amplitude of the input signal, the higher the energy of the signal itself, the easier it is to make a jump between potential wells, and the more the jump period converges to that of the input signal, the closer the output signal waveform is to the input signal waveform.

In the experiments, a large amount of data is generated, and in order to reduce the interference of error factors, the data needs to be processed. The data processing algorithm

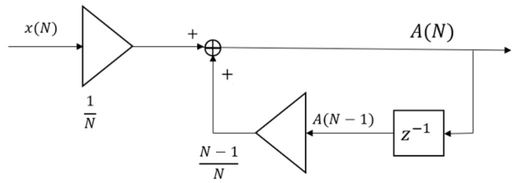

FIGURE 3. Bistable SR system system differential operation.

used in this paper is the recursive averaging algorithm, which can effectively reduce the influence of outliers. Specifically, $A(N-1)$ is the average of the first $N-1$ data, $x(N)$ is the N-th data point, and $A(N)$ is the updated average after including the N-th data point. The calculation formula is:

$$\begin{aligned} A(N) &= \frac{1}{N}\sum_{n=1}^{N} x(n) \\ &= \frac{N-1}{N}\sum_{n=1}^{N-1} x(n) + \frac{1}{N}x(N) \\ &= \frac{N-1}{N}A(N-1) + \frac{x(N)}{N} \end{aligned} \tag{20}$$

In the recursive averaging algorithm, a correction is added to the last calculation based on the new data. As more data is obtained, the number of averages N increases and the value on the right-hand side of equation (20) becomes smaller and smaller, indicating that the impact of the new data on the experimental results is gradually decreasing and the calculated results will gradually converge. When N is large enough, the amount of correction tends to zero, and the data obtained thereafter will have no effect on the experimental results, and the average results will remain unchanged.

IV. SIMULATION ANALYSIS

A. STOCHASTIC RESONANCE SYSTEMS

To verify that the proposed method in this paper can effectively improve the performance of low SNR OFDM systems, the following computer simulation is used to perform stochastic resonance processing on OFDM signals. The simulation platform uses Matlab 2016a.

By taking $a = 1$ and varying the parameter b, we can observe changes in the potential function, as shown in Figure 4. As b increases, the potential well gradually rises and its width becomes smaller. In Figure 5, with a fixed value of b, the potential depth rapidly increases and the width rapidly expands as a increases. The effect of signal amplitude on the generation of stochastic resonance is shown in Figure 6.

Initially, there is no external noise and the particle is located in the right potential well. When the signal amplitude cannot raise enough energy to make it go over the potential barrier, the particle is in the right potential well, and when the signal amplitude can provide enough energy, the particle will go over the potential barrier and oscillate back and forth in the left and right potential wells. The higher the amplitude of the input signal, the higher the energy of the signal itself, the

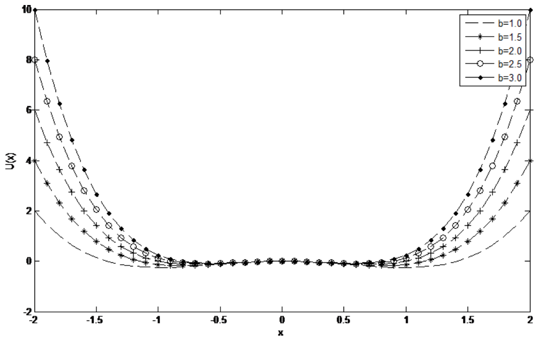

FIGURE 4. The variation of the function when b = 1.

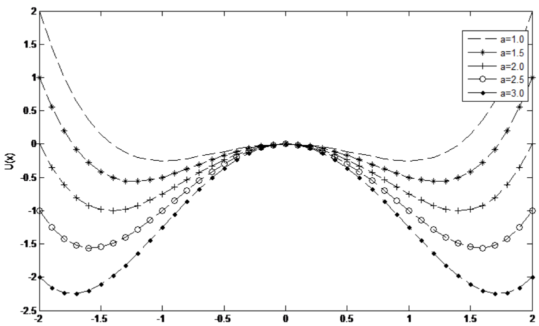

FIGURE 5. The variation of the function when a = 1.

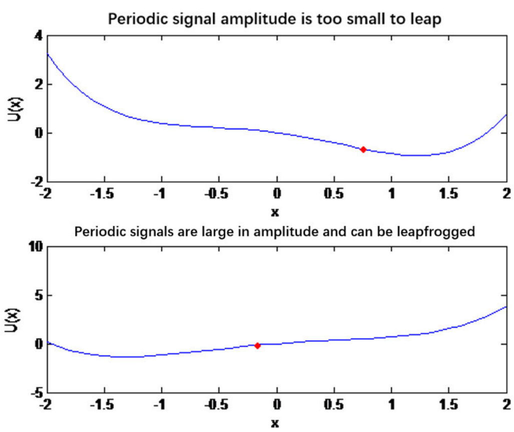

FIGURE 6. Effect of Signal Amplitude on SR.

easier it is to make the leap between the potential wells, and the more the period of the leap converges to that of the input signal, the closer the output signal waveform is to the input signal waveform.

The parameters of the bistable system are set as follows: $a = b = 1$; signal amplitude $A = 0.25$, frequency $f_0 = 0.01$, noise intensity $D = 0.787$, and sampling frequency $f_s = 5Hz$. Simulation analysis of stochastic resonance is carried out, and the waveforms of the input and output signals are shown in Figures 7-8. From Figure 8, it can be seen that the input signal frequency is 0.01Hz, and the output signal has a clear peak at 0.01Hz. The spectral peak is much larger than that of the input signal, indicating that stochastic resonance

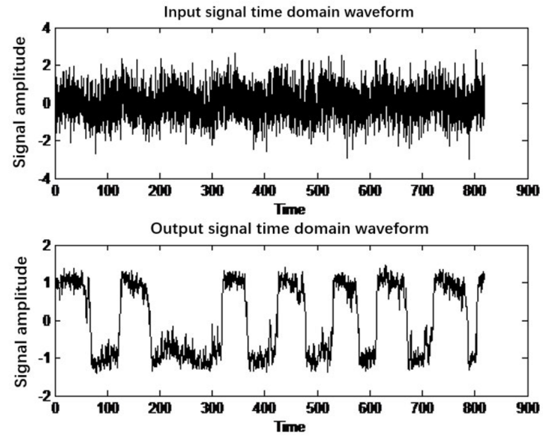

FIGURE 7. Input and output signal time domain waveform.

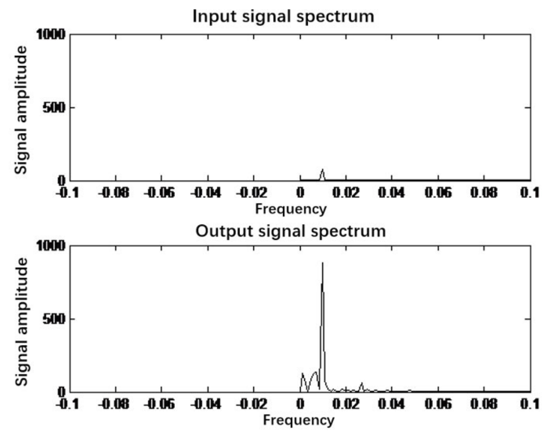

FIGURE 8. Input and output signal frequency characteristics.

has been generated and has a significant enhancement effect on the signal.

B. STOCHASTIC RESONANCE-BASED OFDM SYSTEMS

This experiment uses OFDM signals, and the simulation parameters are set as follows: bit rate of 200 kbps, sampling rate of 20 MHz, 16 bits/symbol, and 16QAM modulation method. The input and received signal waveforms are shown in Figure 9, and a comparison of the baseband code elements and demodulation code elements is shown in Figure 10. It can be observed that the signal after demodulation by the stochastic resonance system is similar to the original signal, and the BER is low.

Output SNR: The output SNR of the system under adiabatic approximation is related to the system parameter b and the noise intensity. The variation of the output SNR with the noise intensity for different b values is shown in Figure 11. It can be seen that the parameter b affects the system output, causing the system output to show a trend of rising and then falling. However, the output SNR will always exhibit a peak, and this peak range represents the optimal noise intensity

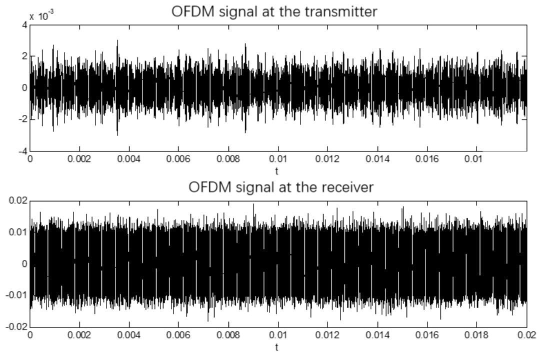

FIGURE 9. Input signal and receive signal.

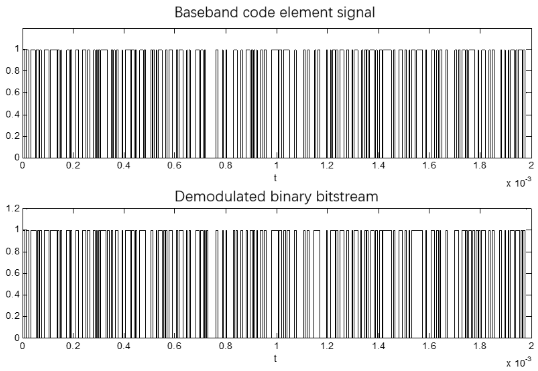

FIGURE 10. Baseband signal and demodulated signal.

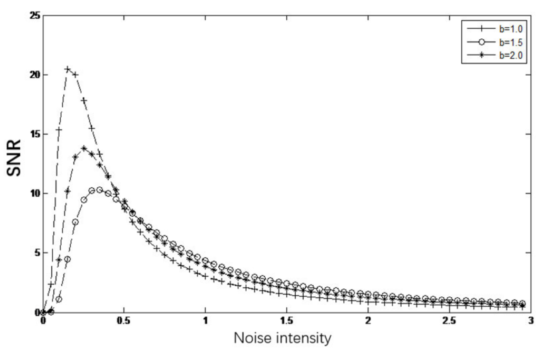

FIGURE 11. Influence of noise intensity on output SNR when adjusting b.

range. By choosing a reasonable parameter to adjust, the system performance can be improved.

The method of stochastic resonance can effectively suppress in-band noise of OFDM systems under low SNR conditions. The experimental results were analyzed and summarized by adding stochastic resonance to the signal through computer simulation. The anti-noise performance of the system was observed before and after the addition of stochastic resonance by analyzing the changes in the constellation diagram of the system and using the BER as a visualization basis. The input SNR was gradually varied to determine whether stochastic resonance could improve the demodulation performance of the OFDM system, according to the changes in the

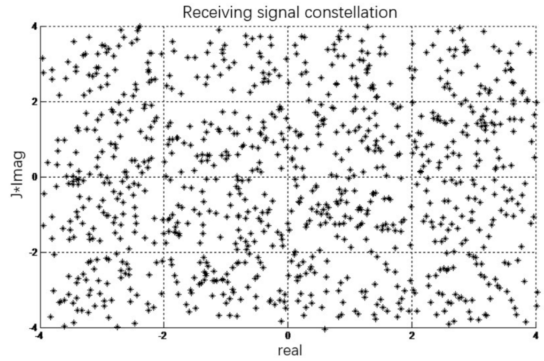

FIGURE 12. Input signal-to-noise ratio SNR = −15.

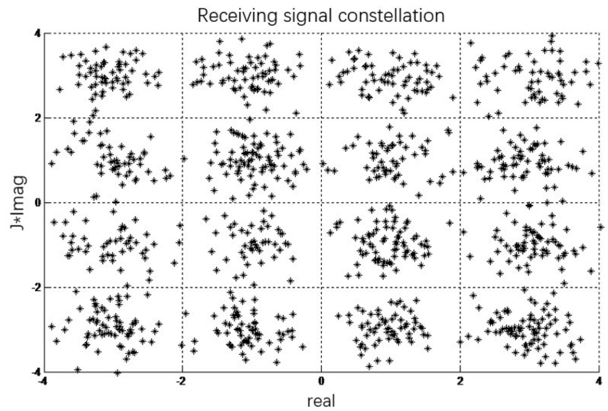

FIGURE 13. Input signal-to-noise ratio SNR = −10.

constellation diagram after the occurrence of the stochastic resonance phenomenon in the system.

Set the system structure parameters $a = b = 1$. Adjust the input SNR gradually to observe the changes in the constellation diagram. In Figures 12-15, when the input SNR is -15dB, the points in the constellation diagram are scattered and not concentrated in the ideal position. As the input SNR gradually increases, the points in the constellation diagram move closer to the ideal points, and the demodulation BER of the system decreases. Within a certain noise range, the demodulation BER of the system is low, indicating that the noise intensity can be adjusted within a certain range to produce stochastic resonance. The parameter that produces stochastic resonance is not a specific value, but a reference value within a range.

The effect of stochastic resonance on the system is shown in Fig. 16. As seen from Fig. 16, when the input SNR of the system is large, the error of the system is large with or without stochastic resonance, indicating that the noise has drowned out the useful signal. As the input SNR increases, the error gradually decreases, but the reduction rate of the stochastic resonance system is much faster than that of the conventional system, indicating that stochastic resonance can effectively improve the performance of the system and the accuracy of signal detection.

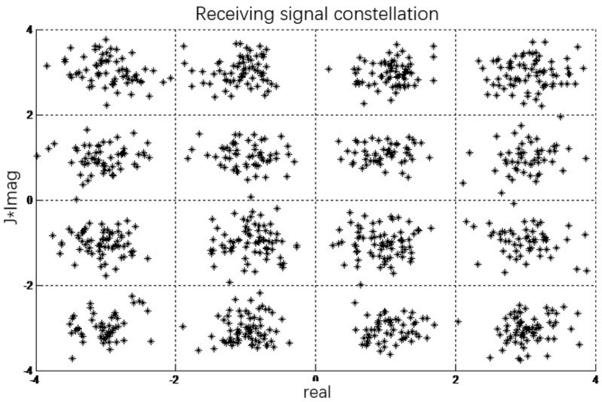

FIGURE 14. Input signal-to-noise ratio SNR = −8.

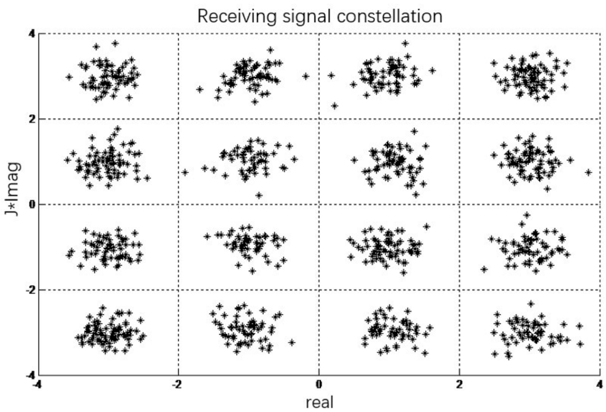

FIGURE 15. Input signal-to-noise ratio SNR = −6.

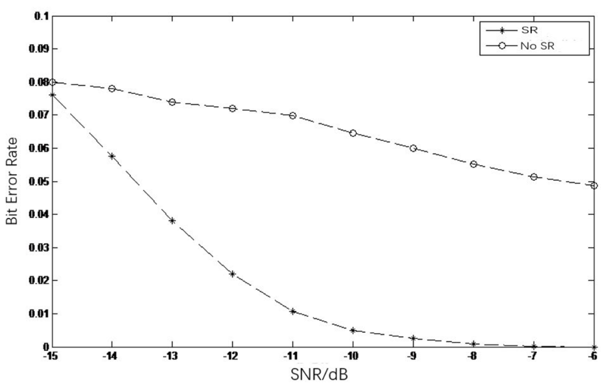

FIGURE 16. Influence of SR on System Demodulation Bit Error Rate.

V. EXPERIMENTAL CONCLUSION

In this paper, a weak OFDM signal detection model is developed to apply stochastic resonance to signal detection under strong background noise. Firstly, the influence of the potential function on the system is analysed, and the input signal threshold at which the stochastic resonance phenomenon occurs is identified. Then, based on the factors affecting the system output (input signal amplitude and noise strength), a parameter adjustment system is designed, and the influence of these factors on the modulation and demodulation of the system under different conditions is analysed. Through experiments, the following conclusions are drawn.

(a)Potential function parameters affect the generation of potential wells and stochastic resonance phenomena in bistable systems.

(b)In the absence of noise, the input signal amplitude needs to be greater than the system threshold($A_{\max} = \sqrt{4a^3/27\,b}$) in order to generate stochastic resonance phenomena.

(c)Adjusting the noise intensity within a certain range can improve the demodulation BER of the system and enhance the quality of communication.

Theoretical analysis and simulation results show that reasonable adjustment of experimental parameters can effectively enhance the energy of weak signals and improve communication quality. The parameter adjustment method is flexible and convenient, and can effectively adapt to the detection of weak signals in various environments, making it highly applicable and promising.

In recent years, with further research on stochastic resonance technology, there have been corresponding breakthroughs in related theories and applications. Zhang [8] conducted relevant research on the performance of multiplicative square wave signals and multiplicative binary noise in stochastic resonance systems, revealing the inherent mechanisms and laws of stochastic resonance, and further discovering the impact of stochastic resonance system parameters on signal transmission and noise suppression. Guo [15] found that within a certain range of noise intensity, the output power of a semiconductor laser feedback system will be significantly enhanced after stochastic resonance induced by noise occurs.

For the study of stochastic resonance phenomena, it is possible to consider combining it with different signals and different filtering methods, and applying it to different scenarios to achieve effective detection of weak signals.

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