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Application of Stochastic Resonance of The Single-Mode Nonlinear Optical System in Spectrum Sensing of Cognitive Radio Networks

Yonghua Wang[1,2,3], Pin Wan[2, 4]*, Qin Deng[2], Yuli Fu[1]
[1] School of Electronic and Information Engineering, South China University of Technology, Guangzhou 510641, Guangdong, China
[2] School of Automation, Guangdong University of Technology, Guangzhou 510006, Guangdong, China
[3] Hubei Key Laboratory of Intelligent Wireless Communications, South-Central University for Nationalities, Wuhan430074, Hubei, China
[4] National Engineering Research Center for Mobile Communication, Guangzhou 510310, Guangdong, China
*Corresponding author, e-mail: wanpin3@ sohu. com

Abstract

The cognitive radio technology can improve the efficiency of spectrum utilization byproviding dynamic spectrum access to unoccupied frequency bands. Spectrum sensing is one of the key technologies of cognitive radio networks. The spectrum sensing performance of cognitive radio networks will be greatly reduced in the low SNR environment, especially when using energy detection. Because the stochastic resonance system can improve the energy detection system output SNR .To improve the spectrum sensing performance of cognitive radio networks in the low SNR environment, the stochastic resonance of the single-mode nonlinear optical system is applied to spectrum sensing based on the energy detection method in this paper. The simulation results show that in the low SNR environment, the energy detection based on stochastic resonance of the single-mode nonlinear optical system has better performance than traditional energy detection.

Keywords*: Stochastic Resonance, Single-mode Nonlinear Optical System, Cognitive Radio Networks, Spectrum Sensing, Energy Detection*

1. Introduction

The Cognitive radio technology can improve the efficiency of spectrum utilization by providing dynamic spectrum access to unoccupied frequency bands.One of the biggest challenges for spectrum sensing (SS) of cognitive radio (CR) networks is detecting the weak primary user (PU) signal in low SNR environment [1]. In low SNR environment, the performance of spectrum sensing will be greatly reduced [2]-[3]. In recent years, some researchers have proposed the application of stochastic resonance (SR) to spectrum sensing in order to solve the problem of detecting weak signal of the primary user. Stochastic resonance refers to the noise energy will be transferred to the signal energy when the input signal and the noise have a match in the non-linear system [4]. At this time, the SNR of the input signal will not be lowered, but will increase. Therefore stochastic resonance is ideal for weak signal detection problem. Stochastic resonance system consists of three elements: a monostable or bistable or multistable nonlinear system, input signal and noise.

In order to improve SNR, He did has applied the bistable SR system to the energy detection in CR in [5]. They also have discussed how to add an optimal SR noiseso that it can improve SNR maximally [6] and the spectrum sensing of CR based on Chaotic Stochastic Resonance [7]. They confirmed that the SR in the colored noise environment is equally applicable [8]. K.Zheng has proposedBlock Spectrum Sensingand Sequential Spectrum Sensing schemes of SR forspectrum sensing in the low SNR regime [9]. Lin Yingpei has proposed a spectrum sensing schemein CRthat combined the cyclostationary feature detection (CFD) and SR [10]. Chen Wei in order to maximizing detection performance, has proposed a generalized SR method in the local sensing and cooperative sensing [11]-[12]. In addition, the covariance matrix [13], cyclostationary [10] and cooperative spectrum sensing [14]-[15] based on the SR have been confirmed that can improve spectrum sensing performancein a low SNR environment.

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The present researches on spectrum sensing based on stochastic resonance are all based on traditional bistable stochastic resonance, and the nontraditional stochastic resonance is not involved. Due to stochastic resonance systemof the single-mode nonlinear optical system can improve the output SNR; it is applied to spectrum sensing based on the energy detection method of Cognitive Radio (CR) networks in order to improve the performance of the energy detection under low SNR in this paper.

2. The Application of nonlinear single-mode optical stochastic resonance system in the energy detection

2.1. Energy detection

Because the energy detection has the following advantages: need not to know any prior knowledgeof the primary users (PU), low computational complexity and easy implementation, thus it is widely used in the cognitive radio spectrum sensing. According to the Neyman-Pearson criteria, spectrum sensing problem can be formulated as the following two assumptions:

$$\begin{aligned} H_0 &: r(t) = n(t), \qquad (t = 0, 1, ..., N-1) \\ H_1 &: r(t) = s(t) + n(t), (t = 0, 1, ..., N-1) \end{aligned} \tag{1}$$

Where H_1 indicates that the PU exists while H_0 shows that the PU does not exist. $r(t)$ is the received signal of the SU. $s(t)$ is the PU signal and is assumedwith zero mean and variance σ_n^2 . $n(t)$ denotes the Gaussian noise and is assumed to be an i.i.dGaussian random process with zero mean and variance σ_n^2 .The signal $s(t)$ and the noise $n(t)$ are assumed independent of each other.

The energy detection model based on stochastic resonance is shown in Figure 1 [4].

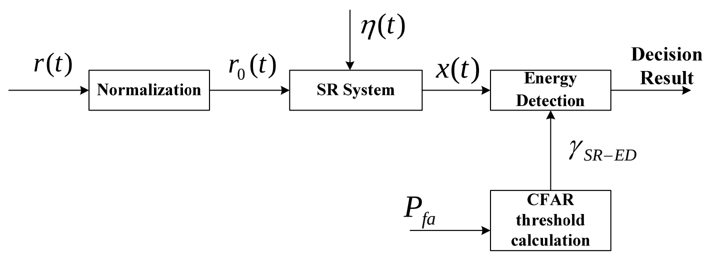

Figure 1. The energy detection model based on stochastic resonance

2.2. The nonlinear single-mode optical system

Ref. [16] studied the behavior of a single-mode stochastic resonance nonlinear optical systems using linear response theory. Based on this research, Wan PIN further studied the stochastic resonance phenomenon of SNR gain in such a single-mode nonlinear optical system (SMNOS), and verified through simulation:in the case of the signal and the noise input at the same time, the system SNR can reach a higher value [17]. The single-mode nonlinear optical system is applied to the energy detection of cognitive radio system to enhance the detection performance of the conventional energy detector in this paper.The phenomenological kinetics equation of single-mode nonlinear optical system with six potential functions is:

$$\dot{x} = -\frac{x^5}{5} + \frac{(1+C)x^3}{3} - Cx + y + n(t) \tag{2}$$

Where C is the system parameter, y is dimensionless incident light field, x is dimensionless outgoing light field, $n(t)$ is the introduced Gaussian white noise, and satisfies $E[n(t)] = 0$, $E[n(t)n(t+\tau)] = 2D\delta(t-\tau)$,where D is the noise intensity. With the change of parameters of C and y , the system defined by formula (2) will be in the monostable, bistable and tristable state respectively, the specific distribution as shown in Figure 2. According to the literature [16], when C are 0.3, -0.1, and 0.1, the system will in the monostable, bistable, tristable steady staterespectively.

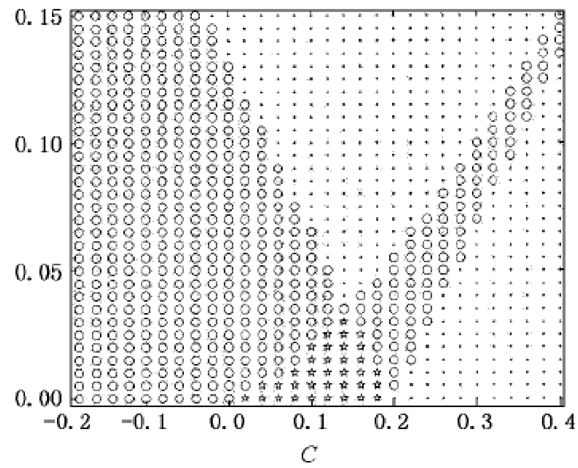

Figure 2. The distribution of the stable fixed point on parameter plane (·Monostable, ○Bistable, ☆Tristable)

3. Experimental Procedure

Detection performance is discussed in the situation that under different false alarm probabilities condition while same SNR, and in the situation that under different SNR while same false alarmprobability. The Monte Carlo method is used, specific steps are as follows:

3.1. Different false alarm probabilities while same SNR

(1) According to binary hypothesis, the received signal is divided into two cases: H_0 and H_1. The received signal is performed *N*-point sampling, and then processed by stochastic resonance system.

(2) According to the energy detection principle, received signal energy values E_0 and E_1 in two hypothetical scenarioswere calculated,then the *n* cyclescalculations are carried out.

(3) After *n* cycles of calculations, the resulting E_0 and E_1 will be stored in the array $a[E_{01}, E_{02}, E_{03}, \ldots, E_{0n}]$ and $b[E_{11}, E_{12}, E_{13}, \ldots, E_{1n}]$.Then array $a[E_{01}, E_{02}, E_{03}, \ldots, E_{0n}]$ is arranged in ascending order, and be saved to another array $\gamma[\gamma_1, \gamma_2, \gamma_3, \ldots, \gamma_n]$ as threshold values.

(4) Calculate the numbers that the elements in the array $a[E_{01}, E_{02}, E_{03}, \ldots, E_{0n}]$ greater than the threshold value $\gamma_1, \gamma_2, \gamma_3, \ldots, \gamma_n$ respectively, then obtained $L[L_1, L_2, L_3, \ldots, L_n]$. $[L_1/n, L_2/n, L_3/n, \ldots, L_n/n]$ represents a set of false alarm probability $P_{fa}[P_{fa1}, P_{fa2}, P_{fa3}, \ldots, P_{fan}]$,where $P_{fa} \in [0,1]$.

(5) Calculate the numbers that the elements in the array $b[E_{11}, E_{12}, E_{13}, \ldots, E_{1n}]$ greater than the threshold value $\gamma_1, \gamma_2, \gamma_3, \ldots, \gamma_n$ respectively, then obtained $M[M_1, M_2, M_3, \ldots, M_n]$. $[M_1/n, M_2/n, M_3/n, \ldots, M_n/n]$ represents a set of detection probability $P_d[P_{d1}, P_{d2}, P_{d3}, \ldots, P_{dn}]$.

$P_{d1}, P_{d2}, P_{d3}, \ldots, P_{dn}$ represent the detection performance when false alarm probabilities are $P_{fa1}, P_{fa2}, P_{fa3}, \ldots, P_{fan}$ under the same SNR environment.

3.2. Constant false alarm probability under different SNR environment

Steps (1), (2), (3) and (4) are same as above.

(5) Under the condition of constant false-alarm probability, the subscript of γ in the array $\gamma[\gamma_1, \gamma_2, \gamma_3, \ldots, \gamma_n]$ is represented by. γ_u is the corresponding energy detection threshold in a given false-alarm probability. After n times calculations, the resulting energy values E_1 are saved to array $b[E_{11}, E_{12}, E_{13}, \ldots, E_{1n}]$.Then the number M that the elements of $b[E_{11}, E_{12}, E_{13}, \ldots, E_{1n}]$ greater than γ_u is calculated. M/n is the detection probability P_d.

(6) Repeat steps (1) to (5) different SNR environments, the detection probabilities can be obtained under the environments with constant false alarm probability and different SNR.

4. Simulation results

Experimental procedures as previously described. In this paper, without considering channel fading and co-channel interference, parameter settings are as follows:the primary user signal is $A\cos(2\pi ft + \phi)$, Gaussian white noise is $n(t)$,the bistable model is $\dot{x}(t) = ax(t) - bx(t)^3 + A\cos(2\pi ft + \phi) + n(t)$,where $a = b = 1$, $\phi = \frac{\pi}{4}$, $A = 2\sigma_n^2 \cdot SNR_i$, Noise variance $\sigma_n^2 = 1$, Signal frequency f are 0.005 Hz,0.01 Hz,0.02Hz respectively, sampling frequency $f_s = 128f$,sampling point *N=256*, Monte Carlo simulation times is 1000. Compare the traditional energy detection method and energy detection method based onsingle-modenonlinear optical system performanceunder two conditions that at the same SNR different false alarm probability environment or constant false alarm probability different SNR environment. The results are shown in Figures 3-8.

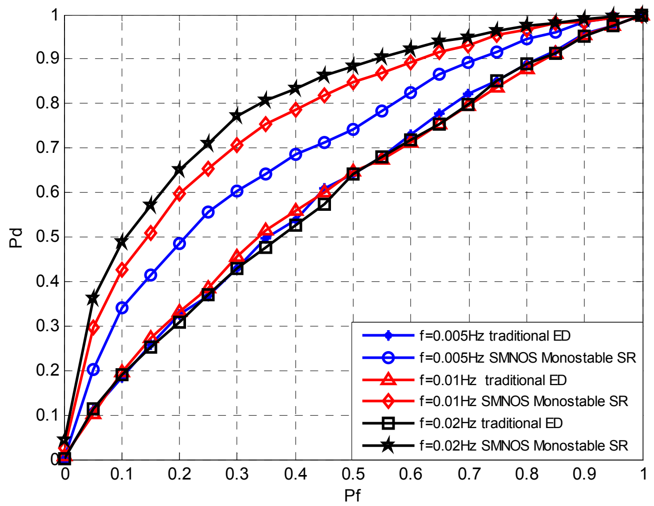

Figure 3. ROC curves of SMNOS monostable SR and traditional ED under SNR=-15dB

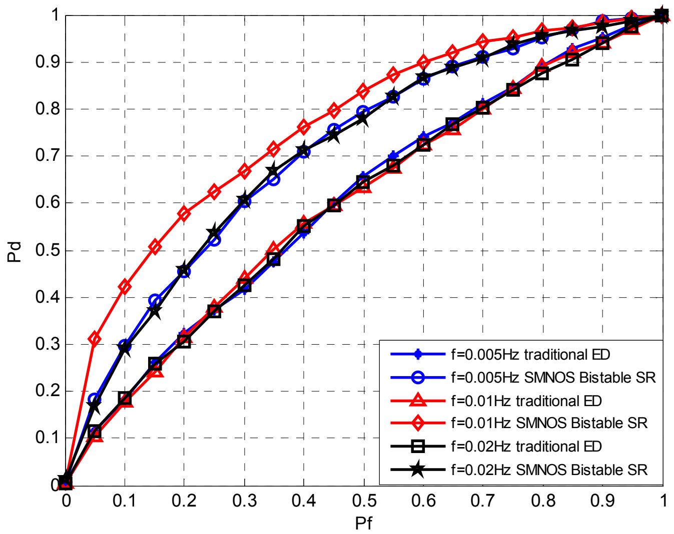

Figure 4. ROC curves of SMNOS bistable SR and traditional ED under SNR=-15Db

Figures 3, 4 and 5 are ROC curves of traditional energy detection and the monostable, bistable and tristable stochastic resonance energy detection of the single-mode nonlinear optical system respectively when the SNR is -15dB.As can be seen from the figures, under various false alarm probability cases, the traditional energy detection performance is not affected by the signal frequency. But the energy detection based on single-mode nonlinear optical system stochastic resonance has different performance with different signal frequencies. And the detection performance of energy detection based on monostable, bistable and tristable system are superior to traditional energy detection.

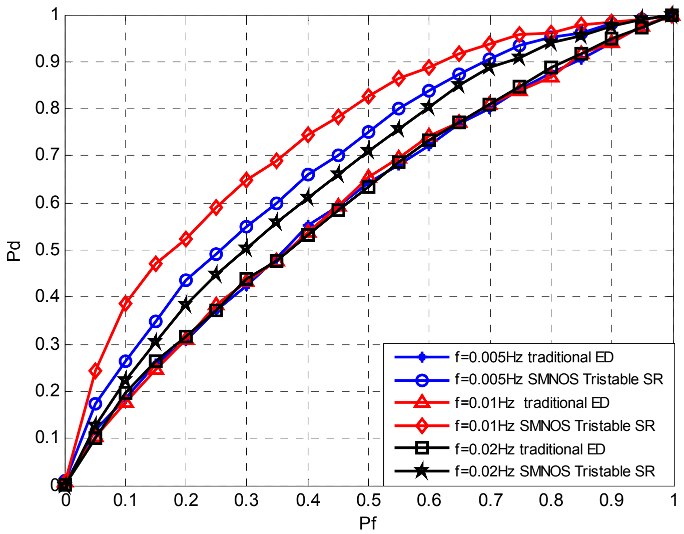

Figure 5. ROC curves of SMNOS tristable SR and traditional ED under SNR=-15dB

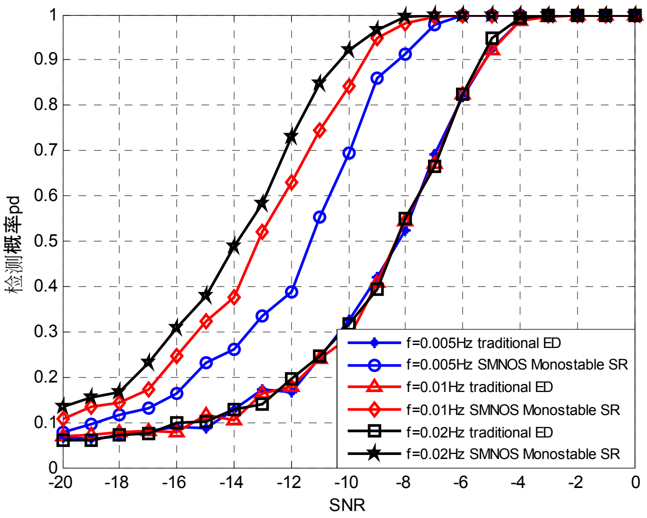

Figure 6. Detection probability versus SNR of different frequencies under $P_{fa} = 0.05$ (SMNOS monostable SR)

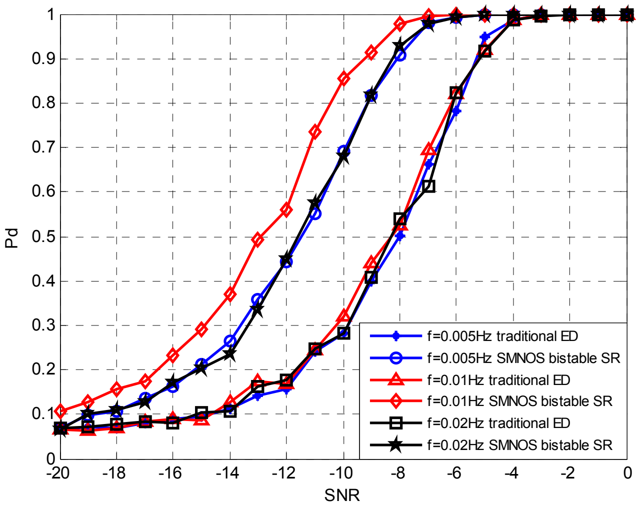

Figure 7. Detection probability versus SNR of different frequencies under $P_{fa} = 0.05$ (SMNOS bistable SR)

Figures 6, 7 and 8 are SNR versus detection probability of the traditional energy detection and the monostable , bistable and tristable stochastic resonance energy detection of the single-mode nonlinear optical system respectively when the $P_{fa} = 0.05$ .As can be seen from the figures, when the signal frequency are 0.005Hz, 0.01Hz and 0.02Hz respectively, in the case of the same SNR, the detection probability of energy detection based on stochastic resonance are higher than the traditional energy detection.

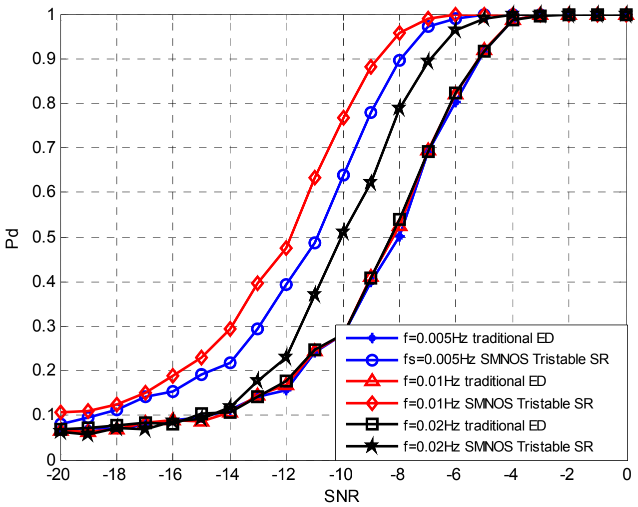

Figure 8. Detection probability versus SNR of different frequencies under $P_{fa} = 0.05$ (SMNOS tristable SR)

5. Conclusions

In this paper, the stochastic resonance of the single-mode nonlinear optical system is applied to energy detection of spectrum sensing in order to increase the system output SNR, thereby enhancing the low SNR environment energy detection performance. Simulation results show that in the case of constant false alarm probability, the detection probability of energy detection based on the stochastic resonance of the single-mode nonlinear optical system is higher than that of the traditional energy detection method, especially in low SNR environment. This research will broaden the scope of application of stochastic resonance, and can increase the detection probability of spectrum sensing under low SNR environment.

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