An Improved Entropy Based Sensing by Exploring Phase Information

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ABSTRACT

In this paper, we present a new sensing method based on phase entropy. Entropy is a measurement which quantifies the information content contained in a signal. For the PSK modulation, the information is encoded in the phase of the transmitted signal. By focusing on phase, more information is collected during sensing, which suggests a superior performance. The sensing based on Phase entropy is not limited to PSK signal. We generalize it to PAM signal as well. It is more advantageous to detect the phase. The simulation results have confirmed the excellent performance of this novel sensing algorithm.

Key Words : Spectrum Sensing, Entropy, Phase, Cognitive Radio

Ⅰ. Introduction

Wireless communication and its applications are undergoing explosive growth nowadays. Due to the increasing demand for additional bandwidths for both existing and new services, there is a spectrum scarcity at frequencies that can be used for wireless communication. To provide necessary bandwidth, a new efficient spectrum assignment policy is essential. The Federal Communications Commission (FCC) has recently permitted opportunistic unlicensed access to the temporarily unused frequency bands across the licensed radio spectrum[1], on the premise of generating minimal interference while taking advantage of the available resources.

As an efficient method to utilize the frequency spectrum, Cognitive Radio emerges into our sight. Cognitive Radio (CR) first proposed by Mitola[2], searches for spectrum white space and offers opportunities to use dynamic spectrum management techniques to prevent interference and adapt to immediate local spectrum availability[3]. In recent years, CR has been exploited and developed by many institutes and academies all over the world.

Cognitive Radio needs to sense the spectral environment and adapt to it. Therefore, spectrum sensing is an essential task for Cognitive Radio. However, there are considerable technical challenges in spectrum sensing. How to enhance the sensitivity of spectrum sensing in a low SNR environment is a hot research issue at institutes and universities.

There exist several sensing methods for Cognitive Radio. The most common three are Match Filtering (MF) based detection, Energy detection (ED)[4,5] and Cyclostationary detection (CSD)[6,7], each of which has their own requirements, advantages and disadvantages. The MF-based detection requires the knowledge of the channel response and synchronization. The ED needs to know the noise variance to differentiate between the noise and signal energy.

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In addition, the performance of ED is susceptible to the noise power uncertainty. CSD has a heavy computation load, thus it is not convenient for many applications.

A novel spectrum sensing algorithm, called Entropy-based sensing, was first proposed by Santosh V. Nagaraj[8]. Shannon entropy[9] is a measure of the average information content. The more regular the variable or signals is, the lower its entropy is. In other words, for a received signal power, the entropy will be maximized if the signal contains only noise. On the contrary, if the signal contains modulated information, the entropy will be reduced. We can test whether the received signal contains information or not by comparing the estimated entropy with a suitable threshold.

In the PSK modulation, all the information transmitted is modulated on phase. If we use the conventional entropy based sensing method, the phase information will be dropped during calculations. We will explain this at section III-A. In contrast, our proposed algorithm can protect the phase information from losing. In addition, phase is not as sensitive to noise as the power of signal. Therefore, combining the characteristics of entropy with the advantages of phase, we propose a new sensing algorithm based on phase entropy. It is more precise and efficient if we test the signal by detecting phase.

Moreover, our phase entropy based sensing has a wide application. We have generalized our method to PAM signal. For PAM signal, it carries information by the variations of amplitude. To manage this case, we map the variations of amplitude to the variations of phase. That will be discussed at section II.

The structure of this paper is as follow: We will introduce the system model of our proposed algorithm in Section II. Then we will analyze the detection ability and present simulation results in Section III and IV respectively, while the conclusions are presented in section V.

Ⅱ. System model and problem formulation

First of all, we give the model of our proposed detector as shown in fig. 1.

In this paper, we assume the primary signal waveform has been known to the CR user. Hence, we can implement a match filter in the receiver. Other modules of this proposed detector will be explained in details next.

Then, we first focus on the primary user(PU) signal which is PSK-modulated. Consider an M-PSK modulated signal which is presented on polar coordinate as [10]:

$$s_m = \sqrt{2E_h}\, e^{j\theta_m}, m = 0,\ldots,M-1 \qquad (1)$$

Where E_h is the energy in band-pass pulse, M is the modulation level. Notice, all PSK waveforms have same energy E_h. To have a clear sense, we plot an 8-PSK signal in Fig.2.

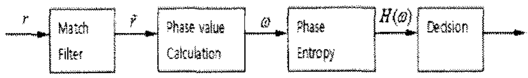

Fig. 1. Proposed phase entropy based detector

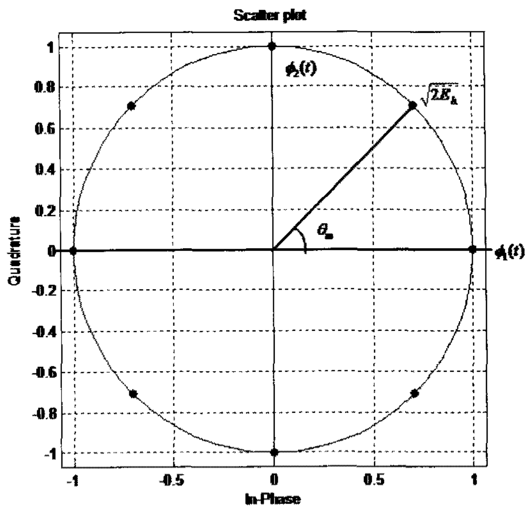

Fig. 2. Complex signal-space diagram for 8-PSK signal

2.1 AWGN Channel

In this subsection, we consider the signal is transmitted in AWGN channel, The received signal is defined as r(t)

$$r(t) = s_m(t) + n(t) \qquad (2)$$

where n(t) is a complex AWGN and $s_m(t)$ is the transmitted signal. Moreover, due to the effect of noise n(t), the exact phase of s_m, i.e., θ_m is unavailable. We can only obtain its approximate estimation $\widehat{\theta_m}$.

$$\theta_m = \hat{\theta}_m + \varepsilon_m \qquad (3)$$

where ε_m denotes the estimation error of θ_m. Assume ε_m is a real white Gaussian noise and further assume the absolute of estimation error ε_m is small enough. In this case, s_m can be rewritten as

$$\begin{aligned} s_m &= \sqrt{2E_h}\, e^{j\theta_m} = \sqrt{2E_h}\, e^{j(\widehat{\theta}_m + \varepsilon_m)} \\ &= \sqrt{2E_h}\, e^{j\widehat{\theta}_m}(\cos\varepsilon_m + \sin\varepsilon_m) \\ &\approx \sqrt{2E_h}\, e^{j\widehat{\theta}_m} + \sqrt{2E_h}\, e^{j\widehat{\theta}_m}\varepsilon_m \end{aligned} \qquad (4)$$

Obviously, $\sqrt{2E_h}\, e^{j\widehat{\theta}_m}\varepsilon_m$ is a complex white Gaussian noise. Define $s_m = \sqrt{2E_h}\, e^{j\widehat{\theta}_m}$. Therefore, Eq. (2) can be rewritten as

$$r(t) = s_m'(t) + n'(t) \quad (5)$$

where $n'(t) = \sqrt{2E_h}\, e^{j\widehat{\theta}_m(t)}\varepsilon_m(t) + n(t)$ is a complex white Gaussian noise. Therefore, the phase estimation error can be equivalently regarded as a kind of channel noise. Therefore, in this paper, we only use Eq. (5) to address the problem, never consider the effect of the phase estimation error.

We plot the constellations for the signal transmitted in AWGN Channel at different SNR in fig. 3 and fig. 4, from which you can observe intuitively how noise effects to the primary signal.

Noise and phase detection errors will cause the phase variations. Due to these variations, the false alarm and the miss detection will occur. When false alarm occurs, a spectrum opportunity is overlooked by the detector and wasted if the SU trusts the sensing outcome. On the other hand, miss detections may lead to collisions with PU. In practice, we are difficult to avoid these. However, our proposed method can reduce the probability of false alarm and the probability of miss detection, comparing with the conventional entropy based sensing method. Our simulation results will be showed in Section IV.

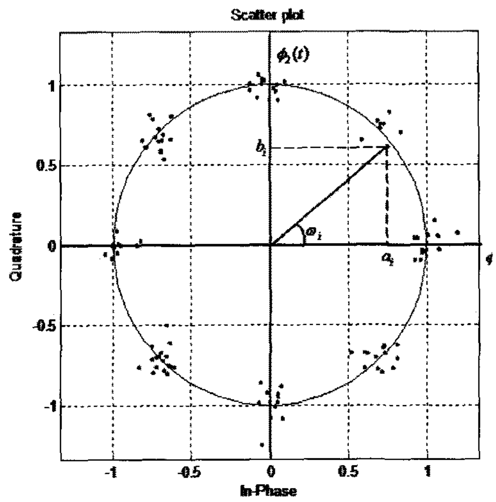

Fig. 3. Received signal (8PSK modulated, SNR=20)

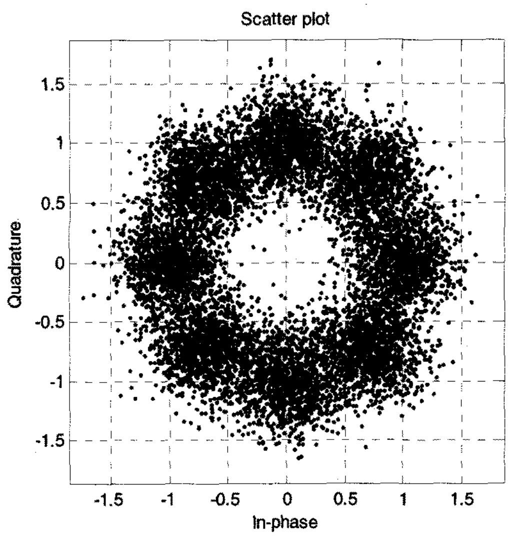

Fig. 4. Received signal (8PSK modulated, SNR=10)

2.2 Phase Entropy estimation

Instead of polar coordinate , we can expressed the received signal on the orthogonal coordinate (see fig. 3 as below:

$$r(t) = a_i\phi_1(t) + b_i\phi_2(t) \qquad (6)$$

The phase of the received signal w_i can be obtained by:

$$w_i = \arcsin\left(\frac{a_i}{\sqrt{a_i^2 + b_i^2}}\right) \quad (7)$$

In our proposed detector, the phase will be calculated in the module following the match filter(see fig. 1).

In information theory, Shannon entropy quantifies the information contained in a message[11]. The entropy H of a discrete random variable X with possible values {x1, ..., xn} is:

$$H(X) = -\sum_{i=1}^{n} p(x_i)\log_2 p(x_i) \quad (8)$$

p denotes the probability mass function of X. From (8) and the principle of maximum entropy[12], the entropy will be maximized when the random variable X is uniform distribution.

There exist some approaches for entropy estimation, such as Histogram[13], Kernel PDF approximation and modified Vasicek's estimator[14]. As far as the complexity is concerned, we will use the Histogram approach in this paper. In the case of Histogram, phase entropy denoted by H(w) is defined as

$$H(w) = -\sum_{i=0}^{k-1} n_i/N\log_2(n_i/N) \quad (9)$$

The parameters will be explained as follows: For histogram approach, we divide the range of phase ω ($w \in [-\pi, \pi]$) into k bins. The bins have equal width of $\triangle = 2\pi/k$, and centers located at $(i+\frac{1}{2})\triangle$, i=0,1,···,k-1. n_i represents the number of the phase value bracketed by i-th bin. N is the total number of phase, i.e. $N = \sum_{i=0}^{k-1} n_i$. Hence, n_i/N denotes the probability distribution in i-th bin.

According to Fig. 3, we can plot the phase distribution of 8PSK signal by histogram as follow:

As it is 8PSK modulated, from Fig. 5, we can find the samples of received signal are distributed around $-\pi, -\frac{3\pi}{4}, -\frac{\pi}{2}, -\frac{\pi}{4}, 0, \frac{\pi}{4}, \frac{\pi}{2}, \pi$. Therefore, we can calculate n_i/N according to this histogram and the phase entropy can be calculated according to (9). This procedure is completed in the third module of our proposed detector(see fig. 1).

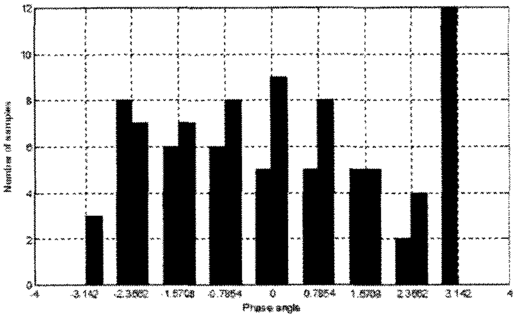

Fig. 5. Distribution of the phase of the received signal

2.3 Detection Strategy

Using above knowledge, we know the phase entropy H(w) is inversely proportional to Signal-Noise-Ratio and H(w) is maximized when the received signal contains only noise. Hence, let two hypotheses h_0, h_1 denote:

$$\begin{cases} h_0 : PUis\ present,\ H(w) < threshold \\ h_1 : PUis\ absent,\ \ H(w) \geq threshold \end{cases} \quad (10)$$

We can detect the primary user using rule (10). When choosing the threshold, there is a tradeoff between false alarm and miss detection. If the threshold is set large, the probability of detection (P_d) will be high, but the probability of false alarm(P_f) is also high. In this sense, if CR trusts the false alarm, that is a waste of spectrum opportunity. [15] has been proved that the threshold which makes Pd equal to Pf is optimal.

In particular, we extend our method to PAM signal as well. In PAM signal, the information is modulated in the amplitude. We map the amplitude of received signal to the phase as Table 1. After mapping, we also use Histogram approach to calculate the phase

Table 1. Map the amplitude to the phase (M is the modulation level)

Amplitude value	Phase value
M	Mπ
M-1	(M-1)π
⋮	⋮
-(M-1)	-(M-1)π
-M	-Mπ

entropy as mentioned above.

Ⅲ. Detection Ability

3.1 Phase information protection

Conventional entropy based sensing method is based on the entropy of the estimated empirical power of received signal samples. As we know, calculating the power is equivalent to calculating the energy of a sample. Here, the conventional method has some disadvantages. Consider the signal:

$$\begin{aligned} &A(t)\sin[2\pi f_c t+\theta(t)] \\ &= a'(t)\sin(2\pi f_c t)+b'(t)\cos(2\pi f_c t) \end{aligned} \tag{11}$$

Where f_c represents a carrier frequency, and

$$\begin{cases} a'(t)=A(t)\cos[\theta(t)] \\ b'(t)=A(t)\sin[\theta(t)] \end{cases} \tag{12}$$

The phase information contained in $\theta(t)$ will be lost when calculating the energy, for instance, Energy= $\sqrt{a_i'^2(t)+b_i'^2(t)}$. In contrast, according to (7) and (8), we can rewrite formula for estimating entropy as

$$H(\omega)=H\left[\arcsin\left(\frac{a_i}{\sqrt{a_i^2+b_i^2}}\right)\right] \tag{13}$$

Phase information will be reserved in the process of calculation. Therefore, our proposed phase entropy sensing algorithm is able to protect the phase information.

3.2 Excellent performance in low SNR

The phase entropy of received signal which contains PU signal is much lower than that of only noise. Thus, that provides a great gap between noise and the received signal containing PU signal. We can use this characteristic to detect PU signal in received signal even in low SNR

Additionally, The more information is collected, the more accurate detection performance is attained. From (11), both the phase and amplitude of received signal are considered in measuring entropy. In other words, more information is collected in our sensing method than the conventional sensing algorithm. Benefiting from this, the accuracy of detection is highly increased. That is, the probability of false alarm is lower down, which has been confirmed in the following simulation

3.3 The multipath fading channel case

Though the case of multipath fading channel is not considered in the previous sections of this paper, our proposed method can also adapt to this case.

When a signal is transmitted in multipath fading channel, it's phase is disturbed by delay additionally, which causes false alarm and miss detection. There exist several anti-fading techniques, such as Equalization, Compensation. These techniques are often implemented in demodulators to give a better BER performance.

However, we would not likely to used the anti-fading techniques in our detector to compensate for phase distortion. As is well known, CR is permitted unlicensed access to white space in some bands, usally the TV bands, on the premise of no interference to license users. For legal issues, as a kind of unlicensed access, CR should ensure the information security of licensed users. Hence, CR should not concern about the demodulation of the received signal If not, the Pay television signal could be demodulated illegally. As spectrum sensing is a part of CR, it only aims to detect the PU signal exists or not, rather than improving the demodulation performance. On the other hand, for low cost and implementation simplicity, it is not reasonable for the

CR spectrum sensing component to implement the compensation or equalization technique.

In this sense, our proposed detector did not implement above techniques. Our method benefits from that more information is collected and phase is so not sensitive to noise than amplitude, it still has a better performance in multipath fading channel, comparing with the conventional entropy based sensing method. In next section, the simulation results of this comparison will be shown.

Ⅳ. Simulation Result

In this section, simulation results are presented to evaluate the performance of the phase entropy based sensing method. These simulations were based on PSK, PAM signals and carried out under AWGN channel and Multipath fading channel respectively.

4.1 Phase Entropy Distribution

Fig. 6 and Fig. 7 compare the phase entropy distribution of conventional method and proposed method(M-PSK modulation, M=2, 4, 8, 16, in AWGN channel). As expected, the estimated entropy degrades smoothly by increasing SNR. Obviousely, the gaps between noise and PU signal are bigger when using our proposed sensing method. When SNR<-4dB, the conventional entropy based sensing method is difficult to distinguish the PSK signal from the noise. Hence, the PU signal is not able to be detected in this scenario. In contrast, phase entropy

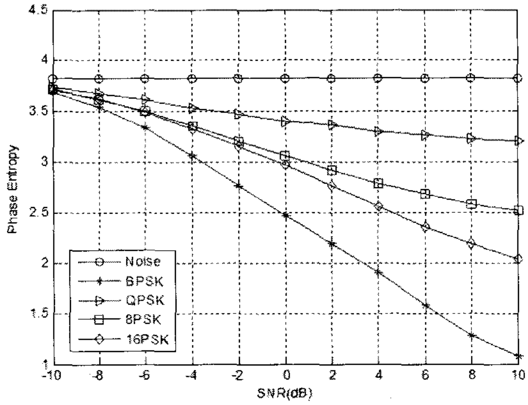

Fig. 7. Phase entropy distribution of proposed sensing algorithm at different SNR for B,Q,8,16 PSK signal

based detector still works in quite low SNR (see Fig. 7). When SNR is lower than -4dB, even up to -10dB, the PU signal can be distinguished.

4.2 Receiver Operating Characteristics (ROC)

We plot ROC for analyzing the performance of two sensing methods. Fig. 8 shows the detection performances of our proposed method and the conventional method at SNR=-4dB. From these two ROC curves, the more bended one indicates a better performance under the same SNR. In particular, we can see that at a fixed probability of false alarm Pf(for instance, PF=0.3),the probability of detection Pd of our sensing method is always higher than that of the conventional method(the conventional Pd=0.4, but our proposed Pd reaches almost 100%). On the other hand, at a fixed Pd, the new method has a

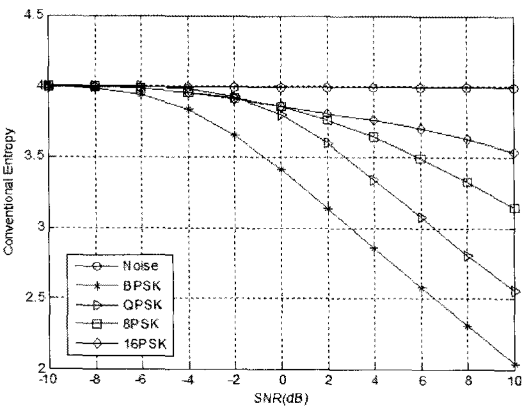

Fig. 6. Engropy distribution of conventional sensing algorithm at different SNR for B,Q,8,16 PSK signal

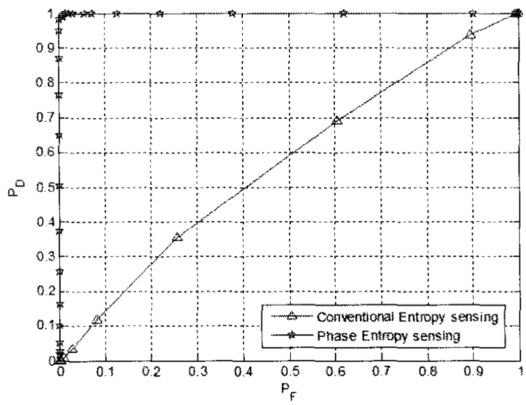

Fig. 8. ROC of conventional sensing and phase entropy sensing at SNR=-4 for QPSK signal

lower probability of false alarm. This indicates our propose method performs a more accurate and reliable detection, comparing with the conventional method.

4.3 Simulations for PAM modulated signal

We also take the experiments on the PAM signals. The distributions of these two sensing methods are provided for comparison. From Fig. 9, 10, we can observe it is more easy to distinguish PU signal and noise by using the phase entropy based sensing method because it has a greater gap. As well, Setting SNR=-4dB, we simulated the ROC curves again, from which we observe the performance of our proposed algorithm is much better.

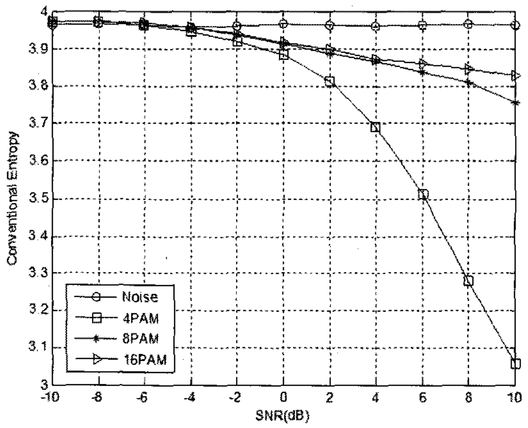

Fig. 9. Entropy distribution of conventional sensing algorithm at different SNR for 4,8,16 PAM signal

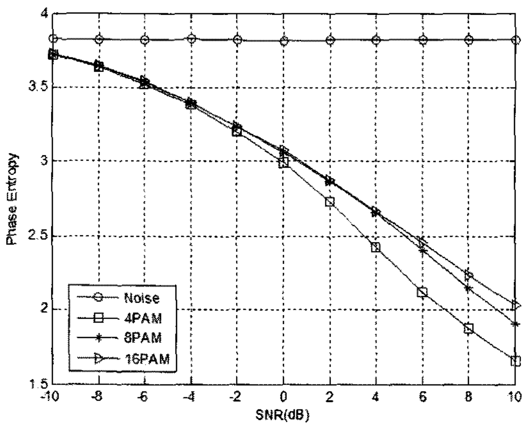

Fig. 10. Phase entropy distribution of proposed sensing algorithm at different SNR for 4,8,16 PAM signal

4.4 Simulation for Multipath fading channel case

In multipath fading channel, the phase varies by the effect of delay and noise. Hence, the detection performance will be not as good as that in AWGN channel. Here, we also plot entropy distribution comparing the conventional method with proposed method(Fig. 12, 13). Moreover, we simulated the ROC for performance comparison(Fig. 14). In these simulations, four-path Reileigh fading is considered. The Arrival time for each multipah is [0, 1us, 1.5us, 2us]. The mean power for each multipath is [0, 10, 20, 25], which means the second path is -10dB less than the first direct path. From these two figures, we can see that using the proposed method, the

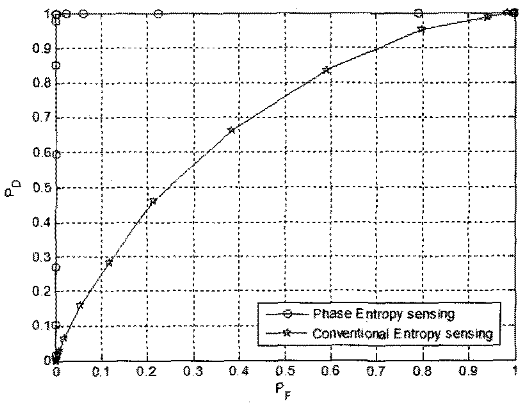

Fig. 11. ROC of conventional sensing and phase entropy sensing at SNR=-4 for 4PAM signal

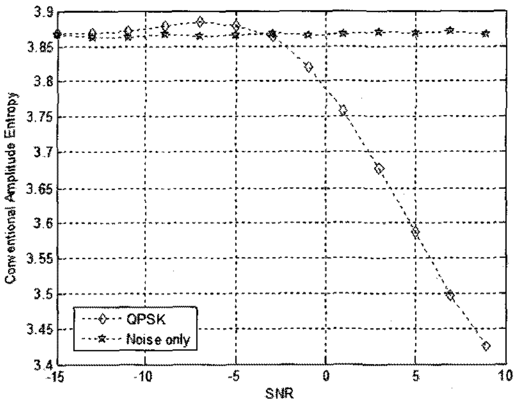

Fig. 12. In multipath fading channel, Entropy distribution of conventional sensing method at different SNR for QPSK signal

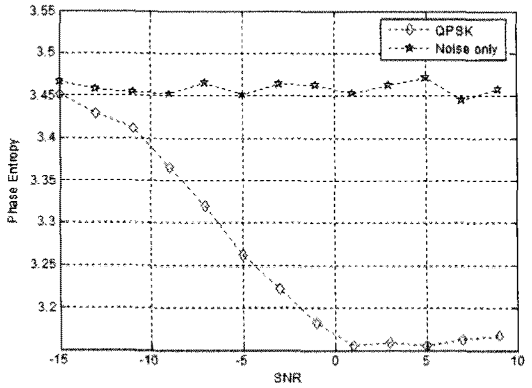

Fig. 13. In multipath fading channel, Phase entropy distribution of proposed sensing method at different SNR for QPSK signal

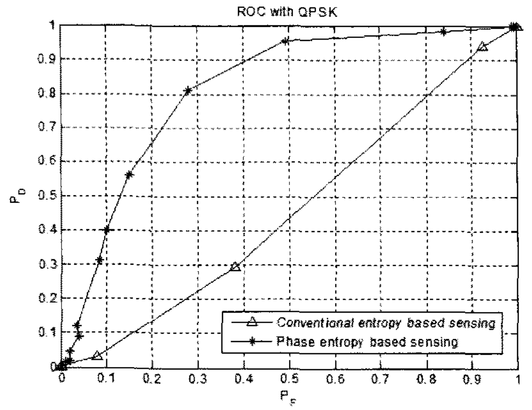

Fig. 14. In multipath fading channel, ROC of conventional sensing and phase entropy sensing at SNR=-4 for QPSK signal

probability of false alarm is reduced and the probability of detection is increased.

V. Conclusion

In this paper, we proposed a new sensing based on phase entropy. As the conventional entropy based sensing method uses the estimated empirical power (amplitudes) of received signal, it has some drawbacks. For example, when the conventional detector calculates the power, it loses the phase information. In addition, power(amplitude) is more sensitive to noise than phase, so the sensing performance is effected by noise seriously. The conventional detector works badly at low SNR.

In contrast, our proposed sensing method exploring phase information. It protects the phase information of the received signal and provides a highly accurate detection. Further more, the phase is not so sensitive to noise, thus this method performs well even in quite low SNR.

The principle of proposed sensing method is based on the principle of Maximum entropy, i.e. the entropy of a distribution is maximum when it is uniform. In this sense, the phase variation produced by noise or by multipath is also uniform distributed. However, amplitude variation produced by noise is Gaussian distributed while that produced by multipath is Rayleigh distributed. Therefore, under multipath fading channel, we are more easier to simulated the affect of noise and channel by using our proposed method.

Finally, it is not difficult to predict that in the future we might utilize the frequency information to detect the primary signal as well. What is more, we may imagine that these sensing algorithms can cooperate with each other to enhance the performance of each other.

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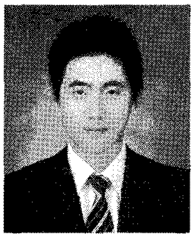

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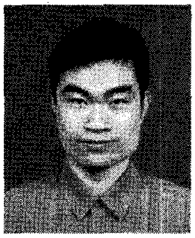

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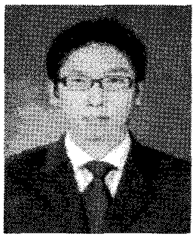

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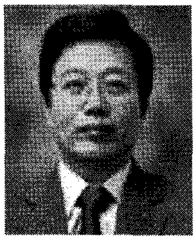

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