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Threshold Optimization Based on Energy Detection in Cognitive Radio Networks

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ABSTRACT

Cognitive radio deals with the efficient management of spectrum resources. Cognitive radio technology allows the unlicensed user to access the licensed band when it is not used by the licensed users. Spectrum sensing function of cognitive radio aims to increase the detection performance by reducing false alarm and misdetection rate. Energy detection technique is adopted for spectrum sensing since it doesn't require any prior knowledge about primary user. An adaptive optimal threshold is formulated that minimizes the sensing error thereby increasing the detection performance under noise uncertainty environment.

INTRODUCTION

In recent years, the rapid growth in wireless service increases the demand for the frequency spectrum (Razavi, B., 2010). The available spectrum is underutilized due to the static allocation of the spectrum. An efficient solution to overcome the under utilization of the spectrum band is cognitive radio technology which is defined by software defined radio (Mitola III, J., G.Q. Maguire Jr, 1999). Among various functions of cognitive radio, spectrum sensing is the crucial function as it involves the detection of primary user(licensed user) signal so that the secondary user(unlicensed user) can access the unused spectrum to maximize the spectrum utilization. Various spectrum sensing techniques include Energy detection, Matched filter detection and Feature detection and so on (Yücek, T., H. Arslan, 2009). Matched filter detection and Feature detection requires prior knowledge about the primary user signal, which is hard to realize practically, since primary users differ in different situations. Energy detection does not require prior knowledge of primary user signal. It is simple and not complex compared to matched filter and feature detection, hence it is easy to implement. The performance of the energy detection scheme lies on how efficiently it detects the primary user. Energy detection method aims in increasing the detection probability and decreasing the false alarm and miss detection probability (Shen, B., 2008). Threshold determination in the energy detection plays an important role in reducing probability of false alarm (P_f) and miss detection (P_m). If the threshold is set to a low value the miss detection probability is reduced, thus the interference to the primary user is minimum. Low value of threshold implies that the probability of ‘spectrum occupancy’ decision is more which reduces the spectrum utilization and hence P_f increases. When threshold value is high, it is difficult to find the spectrum occupancy hence the secondary user can access the channel frequently which increases the spectrum utilization thus the false alarm probability is reduced. The secondary user access can cause interference to the primary user which inturn increases the miss detection probability. Performance of energy detection degrades under low SNR and noise uncertainty environment.

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II. System model:

Energy detection is the common method for the detection of unknown signals in noise.. It is also known as non-coherent detection mechanism (Chen, Y., 2010). The block diagram of energy detector is given in Figure 1.

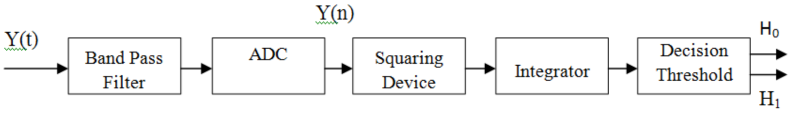

Fig. 1: Block diagram of energy detector.

Energy detector is implemented in the cognitive radio terminal. The Energy detector measures the energy of the signal received from the primary user band. The received signal is passed through band pass filter to remove the noise and it is passed through the squaring device and Integrator. The output from the integrator is then compared to a predefined threshold in the decision device. The decision device depicts the presence or absence of primary user. If the energy of the signal is greater than the threshold value, it indicates the presence of primary user. If it is less than the threshold value, the primary user is absent, hence the secondary user can access the spectrum. Consider y(n) be the received signal at the cognitive radio terminal and x(n) be the transmitted signal at the primary nodes. We assume channel noise w(n) as Additive White Gaussian Noise (AWGN) with zero mean and unit variance and number of samples as N. Let γ be the SNR of the cognitive radio system. The general hypothesis to indicate the availability of the primary user is formulated as,

$$\begin{cases} H_0 : y(n) = w(n) & , n = 1,2, \ldots \ldots, N \\ H_1 : y(n) = x(n) + w(n) & , n = 1,2, \ldots \ldots N \end{cases} \qquad (1)$$

H_0 denotes the absence of primary user and the spectrum can be used by secondary user and H_1 denotes the existence of the primary user i.e the sensed band is occupied.The performance metrics of the energy detection are defined as follows.

2.1. Probability of detection (P_d):

It detects the exact status of the channel.

2.2. Probability of false alarm (P_f):

The channel is detected as occupied when the channel is vacant. It reduces the chance to access the channel when it is free

2.3. Probability of miss detection (P_m):

The channel is detected as vacant when the channel is occupied. It causes interference to primary user, as the secondary user attempts to access the channel.

The output of the integrator is called test statistics (T_s) and it is compared with the predetermined threshold λ to decide the availability of the primary user in the licensed band

$$T_s = \frac{1}{N}\sum_{n=1}^{N} |y[n]|^2 \gtrless_{H_0}^{H_1} \lambda \qquad (2)$$

Assuming the noise variance to be fixed, according to the Central Limit Theorem the test statistics is approximated as a Gaussian distribution.

$$T_s \sim \begin{cases} Normal(N\sigma_n^2, 2N\sigma_n^4) & H_0 \\ Normal(N\sigma_n^2(\gamma+1), 2N\sigma_n^4(\gamma+1)^2) & H_1 \end{cases} \qquad (3)$$

where σ_n^2 represents the noise variance and P represents the average signal power.

Probability of detection defines the probability of detecting the presence of the primary user correctly, when the received test statistics is greater than the threshold indicating the hypothesis H_1. It is determined as

$$P_d = P(T_s > \lambda | H_1) = Q\left(\left(\frac{\lambda}{\sigma_n^2} - \gamma - 1\right)\left(\sqrt{\frac{N}{2}}(\gamma+1)\right)\right) \qquad (4)$$

Probability of false alarm is defined as probability of detecting as the primary user is present when it is actually free under the hypothesis H_0. It is given as

$$P_f = P(T_s > \lambda | H_0) = Q\left(\left(\frac{\lambda}{\sigma_n^2} - 1\right)\sqrt{\frac{N}{2}}\right) \qquad (5)$$

Probability of miss detection is obtained using probability of detection as

$$P_m = 1 - P_d = 1 - Q\left(\left(\frac{\lambda}{\sigma_n^2} - \gamma - 1\right)\left(\sqrt{\frac{N}{2}}(\gamma+1)\right)\right) \qquad (6)$$

Sensing error is represented by less spectral efficiency and interference to the primary user. Let β be the factor that defines the probability about the spectral occupancy and $1-\beta$ indicates that the spectrum is free. Sensing error can be formulated as,

$$P_{se} = \beta P_m + (1-\beta)P_f \tag{7}$$

The number of samples is also an important design parameter to achieve the requirements on detection and false alarm probabilities. From the equations of P_d and P_f by eliminating λ, the number of samples N can be estimated as,

$$N = 2\left[Q^{-1}\left(P_f\right) - Q^{-1}(P_d)(1+\gamma)\right]^2 \gamma^{-2} \tag{8}$$

III. Optimal threshold determination:

Performance of the energy detector lies on the proper threshold set by the system since it determines the probabilities of detection, false alarm and miss detection.

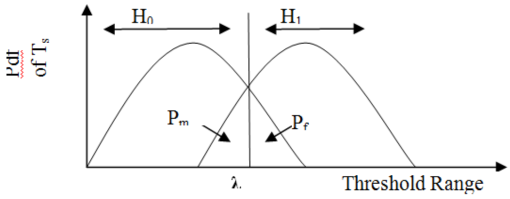

Fig. 2: Gaussian distribution of Test statistics $T_{s.}$

From the Figure 2 it is observed that, if the received test statistics T_s fall is greater than λ it indicates that the spectrum is occupied. If it wrongly depicts as the spectrum is vacant then miss detection occurs .When T_s is less than λ, indicates the spectrum is vacant, but when the detection result wrongly occurs as 'occupied', then the secondary user may not attempt to use the available spectrum, results in increase in false alarm rate. It explains the occurrence of P_f and P_m with the threshold. Spectrum sensing error is defined as a combination of false alarm and miss detection probabilities.

The optimal threshold which minimizes the sensing error under sensing bounds is represented as

$$\lambda^{opt} = \min_{z(t,x)} \lambda \left(PH_0 P_f + PH_1 P_m\right) \tag{9}$$

under $$\frac{d}{dt} = (t,\lambda) = G(z,t,\lambda) \tag{10}$$

where equation (10) is the differential equation for an objective function z(t,x).

The closed form expression for optimal detection threshold is given as

$$\lambda_{opt} = \left(\frac{-\eta+\sqrt{\eta^2-\delta\alpha}}{\delta}\right) \tag{11}$$

$$\delta = \sigma_1^2 - \sigma_0^2 \tag{12}$$

$$\eta = \sigma_0^2\mu_1 - \sigma_1^2\mu_0 \tag{13}$$

$$\alpha = \sigma_1^2\mu_0^2 - \sigma_0^2\mu_1^2 - 2\sigma_1^2\sigma_0^2 \ln\left(\sigma_1/\sigma_0\right) \tag{14}$$

Where $\sigma_{0,}$ $\sigma_{1,}\mu_{0,}$ and μ_1 are considered as per the equation (3).

By using λ_{opt}, obtain P_d, P_f and P_m and it should satisfy the condition given below with the sensing bounds $P_d^{'}, P_f^{'}, P_m^{'}$.

$$P_d = Q\left(\frac{(\lambda_{opt}-\mu_1)}{\sigma_1}\right); \quad P_d \geq P_d^{'} \tag{15}$$

$$P_f = Q\left(\frac{\lambda_{opt}-\mu_0}{\sigma_0}\right) \quad ; \quad P_f \leq P_f^{'} \tag{16}$$

$$P_m = 1 - P_d \quad ; \qquad P_m \leq P_m^{'} \tag{17}$$

Sensing error is calculated using P_f and P_m and is given as,

$$P_{se} = \beta P_m + (1-\beta)P_f \tag{18}$$

IV. Noise uncertainty:

Threshold calculation depends on the noise power. A proper threshold calculation is possible only if noise power is accurately known at the receiver. The estimation error is referred to as noise uncertainty, which can seriously degrade the energy detector performance. Noise uncertainty effect can be studied using estimated noise power, it is assumed to be in an interval $\sigma^2\epsilon[\sigma_{min}^2, \sigma_{max}^2]$.

With noise uncertainty factor, according to the CLT as in equation (3) the test statistics is approximated as a Gaussian distribution and it is represented as

$$T_s \sim \begin{cases} Normal(N\rho\sigma_n^2, 2N\rho^2\sigma_n^2) & H_0 \\ Normal\left(N\sigma_n^2\left(\gamma+\frac{1}{\rho}\right). 2N\sigma_n^4\left(\gamma+\frac{1}{\rho}\right)^2\right) & H_1 \end{cases} \tag{19}$$

Optimal threshold λ_{opt}, Probability of detection, misdetection and false alarm is determined using equation (11-17) with the above modified parameters as in equation (19).

By using the low-SNR approximation and the noise uncertainty effect, the required number of samples for the energy detector to achieve given P_f and P_d can be given as N.

$$N_{min} = \frac{\left[\rho Q^{-1}\left(P_f^{'}\right) - \left(\left(\frac{1}{\rho}\right)(2\gamma+1)\right)Q^{-1}\left(P_d^{'}\right)\right]^2}{\left[\gamma - \left(\rho - \frac{1}{\rho}\right)\right]^2} \tag{20}$$

SNR limit is given as

$$SNR_{limit} = \rho - \frac{1}{\rho} \tag{21}$$

A practical energy detector cannot be implemented at this SNR level, referred to as SNR limit, below which detection is not possible (Tandra, R., A. Sahai, 2005).

V. Adaptive optimal threshold determination:

From the above analysis it is observed that, noise uncertainty may degrade the detection performance. We introduce an adaptive factor with the optimal threshold to mitigate the effect of noise uncertainty[5]. The optimal threshold is made adaptive in the interval as given below.

$$\lambda_{opt}^{'} \epsilon \left(\frac{\lambda_{opt}}{\rho^{'}}, \lambda_{opt}\rho^{'}\right) \tag{22}$$

Where ρ' is the adaptive factor and it should be greater than or equal to 1.

The adaptive optimal threshold is given by

$$\lambda_{opt} = \frac{-\eta + \sqrt{\eta^2 - \delta\alpha}}{\delta} \tag{23}$$

$$\delta = \left(\left((\rho^{'})^2\sigma_1^2\right) - \left(\frac{1}{(\rho^{'})^2}\sigma_0^2\right)\right) \tag{24}$$

$$\eta = \left(\frac{1}{\rho^{'}}\right)\sigma_0^2\mu_1 - \rho^{'}\sigma_1^2\mu_0 \tag{25}$$

$$\alpha = \sigma_1^2\mu_0^2 - \sigma_0^2\mu_1^2 - 2\sigma_1^2\sigma_0^2 \ln((\rho^{'})^2\sigma_1) /(\sigma_0) \tag{26}$$

Detection probability using adaptive optimal threshold and considering noise uncertainty is represented as

$$P_d = Q\left(\frac{\left(\frac{\lambda_{opt}}{\rho^{'}} - \mu_1\right)}{\sigma_1}\right) \; ; \; P_d \geq P_d^{'} \tag{27}$$

False alarm probability and miss detection probability is given as

$$P_f = Q\left(\frac{\lambda_{opt}\rho^{'} - \mu_0}{\sigma_0}\right) \quad ; \quad P_f \leq P_f^{'} \tag{28}$$

$$P_m = 1 - P_d \quad ; \quad P_m \leq P_m^{'} \tag{29}$$

Minimum numbers of samples required for detection under the sensing bounds are given as

$$N_{min} = \frac{\left[\left(\frac{\rho}{\rho^{'}}\right)Q^{-1}\left(P_f^{'}\right) - \left[\left(\rho^{'}\left(\frac{1}{\rho}\right)\left(\sqrt{2\gamma+1}\right)\right)Q^{-1}\left(P_d^{'}\right)\right]^2\right]}{\left[(\rho^{'})^2\left[\gamma - \left(\frac{\rho}{\rho^{'2}} - \frac{1}{\rho}\right)\right]^2\right]} \tag{30}$$

The SNR limit is given as

$$SNR_{limit} = \left(\frac{\rho}{\rho^{'2}} - \frac{1}{\rho}\right) \tag{31}$$

By considering the adaptive factor we could achieve the detection up to the SNR limit, and below which the detection is not possible.

VI. Simulation results:

For Simulation, following design parameters are considered. For modulation, Binary Phase Shift keying (BPSK) is used and the channel is considered to be Additive White Gaussian. Since we consider the sensing error, the false alarm probability is fixed as 0.1.

Figure 3 illustrates the relationship between the number of samples N and SNR Increasing the number of samples under low SNR conditions improves the detection performance, thereby decreasing the probability of error.

Figure 4 shows the effect of noise uncertainty in our proposed method. ρ defines the uncertainty factor and if it is equal to 1, the uncertainty effect is negligible and hence we could maintain the probability of error within 0.2 up to -20dB. Similarly, if we increase the uncertainty factor as 1.04, the noise uncertainty affects the detection performance, hence the SNR limit also increases below which the probability of sensing error reaches the maximum value.

To overcome the noise uncertainty effects, the determined optimal threshold is made adaptive to overcome the uncertainty effect, which is shown in Figure 5. For simulation, the uncertainty is considered as 1.1. When the adaptive factor (AF) equals 1, implies no variations in the optimal threshold, hence noise uncertainty has its effect at SNR around -4dB, the probability of error reaches the maximum value 1 below which the detection is not possible and that defines the SNR limit. In order to overcome the uncertainty effect, the adaptive factor (AF) is increased to 1, then the SNR limit is decreased to around -7dB after which the probability of error reaches the maximum value.

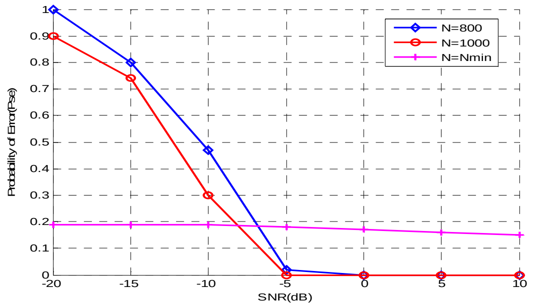

Fig. 3: Probability of sensing error for SNR.

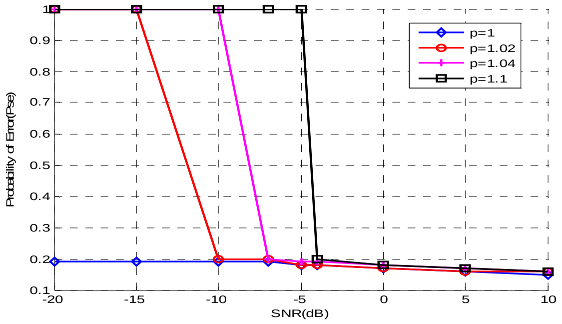

Fig. 4: Effect of noise uncertainty in probability of sensing error and SNR.

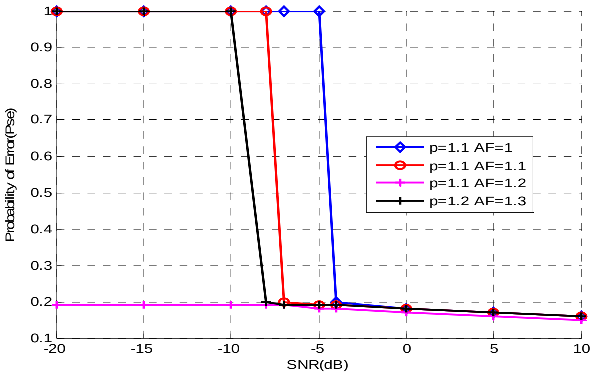

Fig. 5: Probability of error Vs SNR with different dynamic factor.

VII. Conclusion:

An optimal adaptive threshold is determined to reduce the spectrum sensing error and it is also compared with the conventional methods. Effect of noise uncertainty is studied and explained how to mitigate the uncertainty effect using adaptive factor. From the simulation results, it is observed that if noise uncertainty increases even using the adaptive factor in the proposed optimal threshold determination method we could be able to reduce the sensing error

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