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Wide Band Spectrum Sensing Using Window Based Energy Detector For AWGN And Rayleigh Channels

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Abstract

Cognitive Radio is an efficient technique to exploit the underutilized electromagnetic spectrum by introducing opportunistic usage of frequency bands that are not occupied by primary users. Spectrum sensing is a fundamental part of Cognitive Radio systems. A common low complexity technique for spectrum sensing is energy detection, however energy detection is known to fail in the presence of noise uncertainty. In this paper a window based energy detection technique that reduces the noise in the spectrum by averaging the power samples in the frequency domain is proposed to identify the presence of primary users. It is clearly shown that this window based technique improves the detection performance. Moreover the existence of primary users in sub bands of the wideband signal is also identified using this modified method. Simulations based on wideband signals in both fading as well as non fading environment are presented to verify the proposed technique.

1. Introduction

A major challenge in wireless communications is the increased usage of electromagnetic spectrum resource. However the allocated spectrum is found to be significantly inefficiently utilized. Cognitive Radio (CR) is a concept that has been introduced for facilitating more efficient and opportunistic utilization of the available electromagnetic spectrum [1]. CR is characterized by the fact that it can adapt to the environment by changing its operating parameters such as frequency, modulation, format etc. In a CR network the secondary users are the CR users that are allowed to utilize the spectrum when the licensed or primary users are absent. In order to do this, the secondary user should detect the existence of primary user without any error. Spectrum sensing aims to determine the presence of primary users and spectrum availability. Therefore, efficient and effective spectrum sensing is of extreme importance in CR networks.

Spectrum sensing is the ability to measure and sense the parameters related to channel characteristics, power, availability of spectrum, interference and operating environments. A number of spectrum sensing methods are proposed for identifying the presence of primary signal transmission. They can be broadly classified as: Energy detector (ED) [2-5], Matched filter (MF) [5], [6], Likelihood Ratio Test (LRT) [9] and cyclostationarity based detectors [7], [8]. Each of these techniques has different requirements, advantages and disadvantages. Among these techniques LRT [9] is proven to be the optimal, but it is very difficult to use, as it requires exact channel knowledge as well as source and signal distributions, which would be difficult to obtain practically. The Matched filer [5], [6] method requires synchronization and perfect knowledge of channel responses from the licensed primary user. The cyclostationarity based detection [7], [8] requires knowledge of cyclic frequencies of primary users. However energy detection [2-5], unlike the other methods, is a very attractive means of spectrum sensing because of its low computational and implementation complexities. It is a generic method as it does not require any knowledge on the primary user's signal and it is robust to unknown channels and fading. However it requires exact knowledge of noise power [10]. Moreover energy detectors are not robust to noise variance uncertainty.

In this paper, to overcome the shortcomings of conventional energy detectors, an alternative method for wide band spectrum sensing is proposed using the window technique, which reduces or filters out the noise fluctuations in the frequency domain. As this proposed technique reduces the noise fluctuations, it therefore enhances the performance of the detector in the presence of noise uncertainty. The objective of this technique is to smoothen the highly distorted signal by finding the average of the power samples. Similar to the ideal energy detector, this technique also does not require any information about the channel and the primary user signal and, moreover, its performance is significantly good even in the fading channels. Normally an energy detector performs the sensing over the entire wide band and hence sub band detection is not possible. However, in the proposed method, the existence of primary users in the sub bands is also made possible. The novel contribution of this paper includes, the proposal of a technique that is capable of detecting the primary user signal in fading channels and even in the presence of noise uncertainty. Moreover the existence of primary users in individual sub bands is shown to be possible using the proposed method. This paper is organized as follows: In section II, the basic energy detector is explained. The proposed window based energy detector is explained in section III. Simulation results are shown in section IV and the conclusions are drawn in section V.

2. System Model

2.1. Conventional Energy Detector

Energy detection [2-5] is the simplest and the most common technique for spectrum sensing because of its low complexity. The block diagram of an energy detector in frequency domain is shown in Fig. 1. The detector computes the energy of the received signal and compares it to a threshold value to determine the presence or absence of primary user.

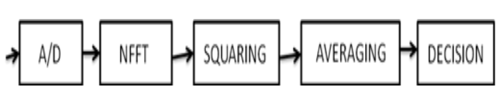

Figure 1. Energy Detector block diagram

In frequency domain, in order to measure the energy of the signal, the received signal is first sampled and these frequency domain samples are obtained by taking an N point fast fourier transform (FFT). The sample coefficients are squared and then average is taken. This decision value is then compared with the threshold. When the decision value of the energy detector is greater than the threshold, the primary user is declared to be present.

Basically the purpose of spectrum sensing is to distinguish between two states: signal presence and signal absence. Let $x_c(t) = hs_c(t) + \eta_c(t)$ be the continuous-time received signal, where $s_c(t)$ is the possible primary user's signal and $\eta_c(t)$ is the noise. Assume we are in interested in a frequency band with bandwidth W. The received signal is sampled at a sampling rate f_s , where $f_s \geq W$ and $T_s = 1/f_s$ is the sampling period. Then, we define $x(n) = x(nT_s)$ as the received signal samples, $s(n) = s(nT_s)$ as the primary signal samples and $\eta(n) = \eta(nT_s)$ as the noise samples. The two hypotheses of the received signal can be stated as:

$$H_0 : x(n) = \eta(n) \quad : \text{ signal absent}$$
$$H_1 : x(n) = hs(n) + \eta(n) \quad : \text{ signal present}$$

H_0 is the null hypothesis meaning that the received signal has noise only. On the other hand, the hypothesis H_1 means that the received signal has both signal and noise, where $s(n)$ is transmitted by the primary users and $x(n)$ is the signal received by the secondary users over a channel with gain h. h is constant when the channel is non-fading . When the channel is fading, h includes fading effects. $\eta(n)$ is the noise vector which contains independently and identically distributed (i.i.d) AWGN samples with zero mean and variance σ_η^2 .

However, the performance of the detector relies highly on the noise level as it uses this as a predefined threshold. The detector is not robust in the presence of noise uncertainty. In practical scenarios, it is not possible to obtain the correct value of noise variance and hence the energy detector fails to operate well. For fading channel also the performance degrades quite significantly thus making the detector ineffective. Therefore an alternative method has been proposed here to relieve the drawbacks and improve performance.

2.2. Window Based Energy Detectors

The improved window based method block diagram is shown in Fig. 2. Here, instead of taking the direct average of the squared received frequency domain signals as in conventional energy detector, a windowing operation is performed on the received signals to reduce unwanted noise fluctuations and hence facilitate the proper detection of the primary user signals.

Figure 2. Window Based Energy Detector Block Diagram

As in section 2.1, using an N-point FFT, the received signal is transformed into frequency domain. The frequency sample X(k) can be given by the Discrete Fourier transform (DFT) equation:

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{j2\pi k/N} \qquad ,0 \le k \le N-1 \qquad (1)$$

In order to reduce the effect of noise fluctuations, a window function is used. Here the entire spectrum is divided into number of windows based on the window size. The power samples P(k) are passed through this window function where the samples, P(k), are obtained by taking the square of each of the samples, X(k). The size of the window can be arbitrarily predefined and is a parameter that can be varied depending on system performance. The jth window function can be defined as

$$z(j) = \frac{1}{w} \sum_{n=1}^{w} P(k) \qquad (2)$$

where w is the window size. When the power samples, P(k), are passed through this window function, the average is calculated and then the function shifts to the next set of samples and so forth to get a smoother curve.

3. Signal Detection

3.1. Detection in non-fading channels

The test static, T_{ED}, for energy detection is given by [15]

$$T_{ED} = \sum_{n=1}^{m} z(n) \qquad (3)$$

where m is the number of windows.

Based on the decision statistics, the threshold can be derived from the formulations for probability of detection (P_d) and Probability of false alarm (P_{fa}) as follows [15]

$$P_{fa} = P(T_{ED} > \gamma \mid H_0) = \int_{\gamma}^{\infty} p_0(t)dt \qquad (4)$$

$$P_d = P(T_{ED} > \gamma \mid H_1) = \int_{\gamma}^{\infty} p_1(t)dt \qquad (5)$$

where $p_0(t)$ and $p_1(t)$ are the probability density functions (PDFs) under the hypotheses H_0 and H_1 respectively and γ is the decision threshold. As a results of the central limit theorem, the test statistic, T_{ED} ,, under hypothesis H_0 , can be approximated as a real Gaussian variable with mean σ_η^2 and variance σ_η^4 / N while T_{ED} , under hypothesis H_1, can be approximated as a real Gaussian variable with mean $(1+\lambda)\sigma_\eta^2$ and variance $(1+2\lambda)\sigma_\eta^4 / N$ where $\lambda = \sigma_s^2 / \sigma_\eta^2$ is the received signal to noise ratio (SNR) of the primary user as measured at the secondary receiver.

The threshold γ can be expressed as follows

$$\gamma = \left(\frac{Q^{-1}(P_{fa})}{\sqrt{N}} + 1 \right) \sigma_\eta^2 \qquad (6)$$

3.2. Detection in Rayleigh fading channels

In fading environment, the distributions and probabilities differ since the SNR can exhibit various distribution [12-14], however specifically, the probability, P_{fa} , remains the same because it is independent of SNR.

The probability of detection for the fading channel can be expressed as [16]:

$$P_{d,fading} = \int_{\lambda} Q_m\left(\sqrt{2m\lambda}, \sqrt{\gamma}\right) f_\lambda(x)dx \qquad (7)$$

where $f_\lambda(x)$ is the probability distribution function of SNR under fading, m is the time-bandwidth product and $Q_m(.,.)$ is the Marcum Q-function.

Under Rayleigh fading, the signal amplitude follows a Rayleigh distribution and hence the SNR follows an exponential PDF, which may be defined as

$$f(\lambda) = \frac{1}{\bar{\lambda}} e^{-\frac{\lambda}{\bar{\lambda}}}, \qquad (8)$$

where $\bar{\lambda}$ is the average SNR.

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4. Simulations

In this section, simulation results will be given for the purpose of comparison with the theoretical expressions given in the previous section. In common with the previous section, two distinct type of channel scenario are considered. These scenarios are:

- Additive White Gaussian Noise (AWGN) ,
- Rayleigh fading.

4.1. Wide Band Signals

The signal under consideration for detection is a digital video broadcast–terrestrial (DVB-T) signal, which has a bandwidth of 8MHz. The sequence of blocks in signal is modulated according to the orthogonal frequency division multiplexing (OFDM) technique using 1705 carriers (2k mode). In the time domain, the duration of data part is 224 microseconds and the guard band part is 56 microseconds (1/4 of the symbol duration).

Here these signals are considered for the case of three primary users occupying different sub bands. The spectrum is shown in Fig.3.

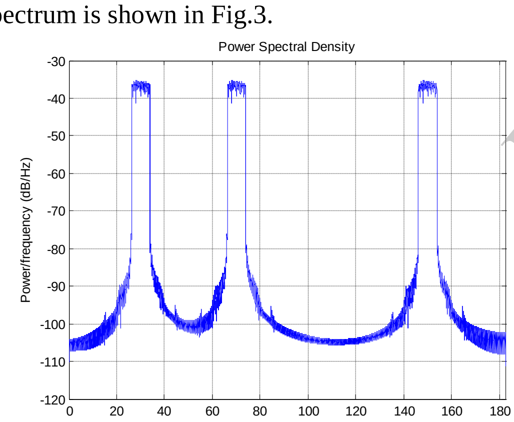

Figure.3 Wide band spectrum

In order to simulate the algorithm at low SNR, AWGN samples are added to obtain various SNRs. After passing DVB-T signals through the window function of the proposed detector, the noise fluctuations in the spectrum are very much reduced. Here the window size is selected to be 50 for the purpose of computationally tractable simulations. The conventional energy detector is not robust in the presence of fading and hence proper signal detection becomes impossible. However, the proposed window based detector is found to be robust even in fading channels. In order to identify the existence of primary users in each sub bands of the wide band spectrum, the entire spectrum is divided into different sections and individual detection is performed in each sub band. If a sub band is found to be empty, then it can be allocated to the secondary or the cognitive user.

4.2. AWGN channel scenario

In Fig.4 the proposed window-based method is compared with the conventional energy detector for the received DVB-T signals for the case of a simple AWGN channel scenario. From the Fig.4 it is clear that the proposed method outperforms the conventional method and the probability of detection is higher than the conventional energy detector at low SNRs, which is the requirement for the CR devices. In Fig. 5 the sample size, N, is plotted against the probability of detection, P_d, for different values of P_{fa}. From the Fig. 5 it is clear that as N increases, the probability of detection also increases.

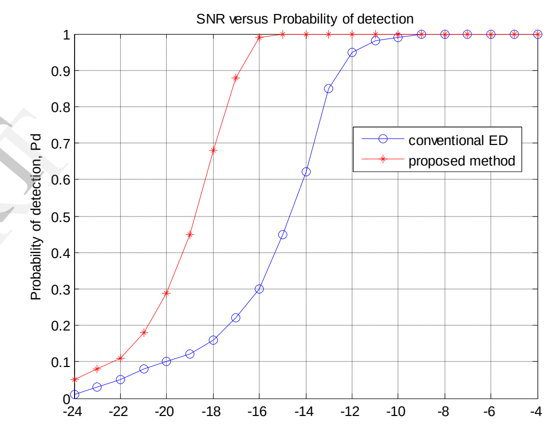

Figure 4. Performance for DVB-Tsignal detection compared to conventional energy detector (P_{fa} = 0.1)

The dependency of the performance with window size for the proposed detector is shown in Fig. 6. It is clear from Fig. 6 that P_d, is higher for high window sizes and performance degrades as the window size decreases. In Fig. 7 ROC curves are plotted for the proposed detector in the presence of noise uncertainty. One of the most important factors that degrade the performance of conventional energy detector is the existence of noise uncertainty. From Fig. 7, it is clear that the performance of the proposed detector is significantly higher when there is noise uncertainty.

One of the biggest advantages of the proposed detector is that it is capable of identifying the presence of primary users in sub bands over a wide bandwidth. For simulation, the entire spectrum is divided into 3 sub bands, each 60MHz in width. From Fig. 8 it is clear that the proposed detector is capable of sensing each sub band individually whereas the conventional energy detector performs sensing over the entire wideband and thus individual sub band is detection is not possible. Detection of users in individual sub bands is an important advantage of this technique. Generally signal detection using Energy Detector [2-5], Covariance Absolute Value method [17], Eigen Value method [18], cyclostationarity method [7], [8] are efficiently done in narrow bands and if comes to wideband scenario they detect the existence of users over the entire range of band. And if multiple users are present in the wide band these detection methods won't individually differentiate or identify each user. But identification of the existence of multiple users in the wideband is essential for the proper efficient working of the cognitive radio devices. And this problem is properly addressed using this technique meeting the target probability of detection requirements of the cognitive radio devices.

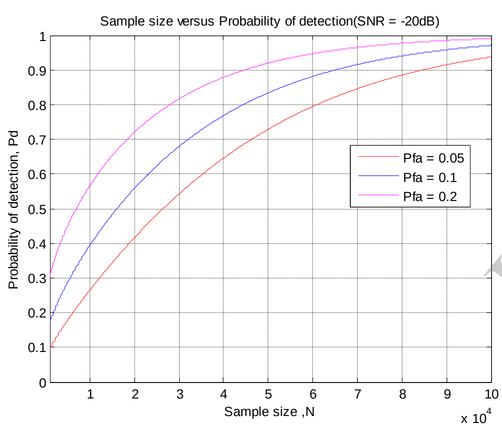

Figure 5. Sample size versus P_d, at different values of probability of false alarm

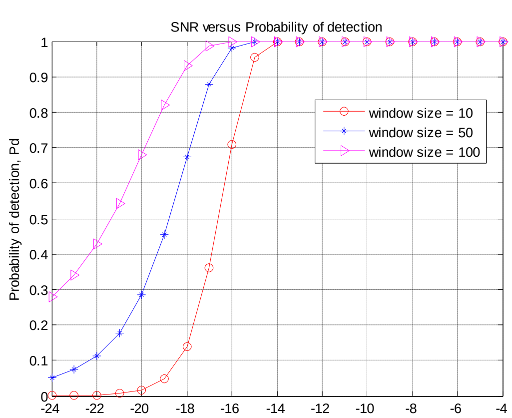

Figure 6. SNR versus P_d, for various window sizes.

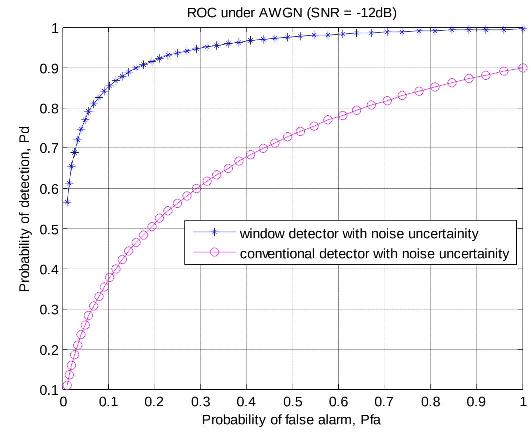

Figure 7. ROC curve in the presence of noise uncertainty

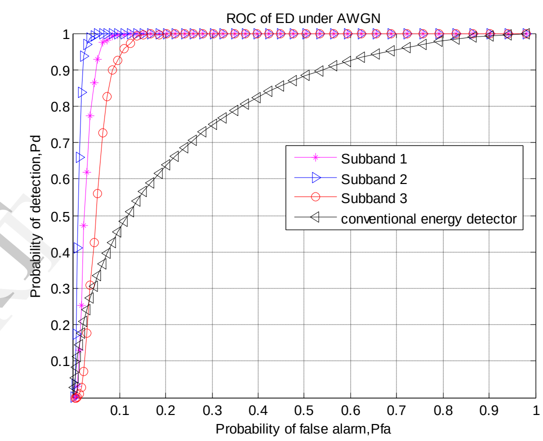

Figure 8. ROC curve showing sub band detection.

4.3. Rayleigh Fading

In this case the received signal reaches the cognitive user or the secondary user after passing through a Rayleigh faded channel. In such a fading environment, spectrum sensing would be hindered by the uncertainty resulting from channel randomness. In such cases, a low received energy may be due to faded primary signal rather than unoccupied signal space [13], [14]. This would result in larger interferences to the primary users. As mentioned in Section 3.2, in a fading environment, the distributions and probabilities vary from the case of the non fading environment and the SNR can exhibit various different distributions. A fundamental parameter that determines the quality of detection is the average SNR, which mainly depends on the primary user's distance to the secondary users as well as its transmitted power. In Fig. 9, the proposed method is compared with conventional energy detector under Rayleigh fading. From the Fig. 9, it is clear that the proposed method outperforms the conventional energy detector and it satisfies the probability of detection criterion for CR devices at low SNRs.

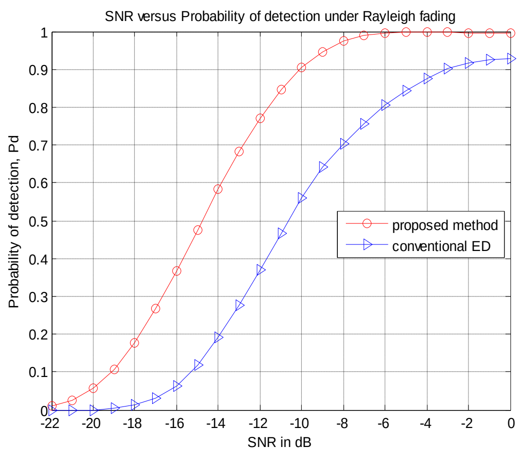

Figure 9. Comparison of performance of DVB-T signal detection for conventional energy detector and proposed energy under Rayleigh fading (P_{fa} = 0.1)

5. Conclusions

Energy detection is an attractive spectrum sensing technique for CR because of its low complexity and ease of implementation. Moreover, it does not require any information about the primary user signal and is robust to channel, delay, frequency offset and timing uncertainty. However, its performance degrades in the presence of noise uncertainty. Thus an alternative energy detector using a window function is introduced to reduce noise fluctuations and perform efficient signal detection. Moreover identification of the existence of multiple users in the sub bands of a wideband signal is also facilitated in this method. The simulation results show that the proposed technique performs efficiently in fading as well as noisy channels and even in the presence of noise uncertainty. It is also seen to meet the required target probability of detection for CR devices. Extending this technique to the cooperative method of spectrum sensing will be the subject of future work.

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