Comparison of Different Spectrum Sensing Techniques for Cognitive Radio Systems

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Abstract—In Cognitive radio networks, the optimum utilisation of the spectrum can be ensured by detecting the unused spectrum by spectrum sensing techniques and sharing it without harmful interference to other users. One important requirement in a cognitive radio network is sensing spectrum holes reliably and efficiently. This paper outlines the different spectrum sensing techniques like matched filter detection, energy detection and cyclostationary feature detection and compares the performance in presence of additive white Gaussian noise. The results are summarized in the concluding section.

Index Terms—cognitive radio, spectrum sensing, matched filter detection, energy detection, and cyclostationary feature detection.

I. INTRODUCTION

Cognitive Radio is a new paradigm of designing wireless communications systems that aims to enhance the utilization of the radio frequency (RF) spectrum. The motivation behind cognitive radio is the scarcity of the available radio frequency spectrum, increasing demand, caused by the emerging wireless applications for mobile users [1]. Some of the different radio frequencies allocated for licensed users in wireless applications in USA for example are 470MHz-800 MHz used for TV signal transmission, 1.7-1.85GHz-1.85GHz, 2.5-2.69GHz for 3G wireless systems. Some of the frequency allocations for unlicensed users in USA are ISM band I for cordless phones, 1G WLANs, ISM band II 2.4-2.4385GHZ for Bluetooth etc. [1]

A study by the Spectrum Policy Task Force (SPTF) of the Federal Communications Commission (FCC) has shown that some frequency bands are heavily used by licensed systems in particular locations and at particular times, but there are also many frequency bands which are also partly occupied or largely unoccupied [2]. This is due to the spectrum licensing scheme where the license cannot change the type of user or transfer the right to other user. Due to static licensing scheme, spectrum holes or spectrum opportunities arise. Unlicensed users can therefore access these spectrum holes, which are not utilized by licensed users. Since the wireless systems, which were already designed to operate on a dedicated frequency band, they are not able to utilize the improved flexibility provided by this new spectrum licensing technique. Thus the concept of cognitive radio has been introduced.

The term “cognitive radio” was defined in [3] as follows: “Cognitive radio is an intelligent wireless communication system that is aware of its ambient environment.

This cognitive radio will learn from the environment and adapt its internal states to statistical variations in the existing RF stimuli by adjusting transmission parameters in real-time and on-line manner.” The main goal of the cognitive radio should be to provide adaptability to wireless transmission through dynamic spectrum access so that the performance of wireless transmission can be optimised, as well as enhancing the utilization of the frequency spectrum [1]. The major functionalities of a cognitive radio system include spectrum sensing, spectrum management and spectrum mobility. In this paper the spectrum sensing functionalities of the cognitive radio is investigated.

II. PRACTICAL SPECTRUM SENSING APPROACHES

The four typical practical spectrum sensing approaches are described below. The objective of spectrum sensing is to detect the presence of transmission from license users. There are three major types of spectrum sensing, namely, non-cooperative sensing, cooperative sensing and interference based sensing. Of these types the paper investigated the non-cooperative spectrum sensing, namely, matched filter detection, Energy detection, cyclostationary feature detection. Non-cooperative spectrum sensing is used by an unlicensed user to detect the transmitted signal from a licensed user by using local measurements and local observations. The model for signal detection at time t can be described by (1) and (2) as

\[
x(t) = n(t) \quad H_0, \quad (1)
\]

\[
x(t) = h(t) * s(t) + n(t) \quad H_1, \quad (2)
\]

where \(x(t)\) is the received signal of an unlicensed user, \(s(t)\) is the transmitted signal of the licensed user, \(n(t)\) is the additive white Gaussian noise, and \(h(t)\) is the impulse response of the channel. Here \(H_0\) and \(H_1\) are defined as the hypotheses of not having and having a signal from a licensed user in the target frequency band respectively [1].

The performance of a spectrum sensing technique can be measured in terms of the probability of correct decision (\(P_{d}\)), probability of false alarm (\(P_{f}\)), and the probability of miss (\(P_{m}\)). Mathematically, \(P_{d} = \text{Prob} \left\{ \text{decision} = H_1 | H_1 \right\}\), \(P_{f} = \text{Prob} \left\{ \text{decision} = H_1 | H_0 \right\}\), and \(P_{m} = \text{Prob} \left\{ \text{decision} = H_0 | H_1 \right\}\).
received signal was plotted. The Power Spectral Density of the received signal from a band pass filter is squared and integrated over the observation interval. A decision algorithm compares the integrator output with a threshold to decide whether a licensed user exists or not. In general the performance of an energy detector deteriorates when SNR decreases. An energy detector is a non-coherent detector that avoids the complicated coherent receivers required by a matched filter, and can be implemented using spectrum analysing tools such as fast Fourier transform (FFT). Although an energy detector is simple to implement, there are several drawbacks. First the spectrum sensing speed is relatively slow. Second, the threshold for detection is very susceptible to the noise level and in-band interference. Third, an energy detector cannot differentiate modulated signals, noise, and interference. As a result, the benefits of detection and interference cancellation techniques cannot be employed. Fourth, the primary user and the secondary user cannot be distinguished. Finally, energy detection does not work for spread spectrum signals [1,5].

B. Matched Filter

Matched filter detection can be used to detect a signal by comparing a known signal (i.e. a template) with the input signal [4]. Since a template should be used for signal detection, it requires very small time to operate. However if this template is not available or is incorrect, the performance of spectrum sensing degrades significantly. A matched filter maximizes the signal-to-noise ratio at the sampling time, if the transmission waveform of the primary user is known.

This requires the secondary users to have a priori knowledge of the primary user signal such as modulation type and order, pulse shaping, and packet format. The secondary users have to be equipped with carrier synchronization, timing devices and even an equalizer. This is possible for some type of primary users such as TV signals and OFDM preambles. Due to the coherent nature of the matched filter, detection can be very fast. But if there are multiple types of primary users, the secondary users have to be equipped with multiple dedicated receivers [1,5].

C. Cyclostationary feature detection

A signal is cyclostationary (in the wide sense) if the autocorrelation is a periodic function. The modulated signals are usually cyclostationary, since built-in periodicity often occurs in training sequence, cyclic prefixes, etc. This periodicity is introduced in the transmitting signal of the primary users so that the receivers can exploit it for timing, channel estimation etc. Also this periodicity can be used for detection of the primary user. The basic approach is based on the autocorrelation function and power spectrum density. The spectral correlation function has a cyclic spectrum with cycle frequency. One advantage is that the noise and interference which are wide sense stationary signals do not exhibit spectral correlation can be eliminated. As a result, the cyclostationary detector can work in a low – SNR region. In general, cyclostationary detection can provide a more accurate sensing result and is robust to variations in noise power [1,5].

III. IMPLEMENTATION

The spectrum sensing techniques listed above namely Energy Detection, Matched filtering, and Cyclostationary detection were implemented in Matlab. A composite signal with different frequencies was taken as a base signal. Additive white Gaussian noise with varying SNR was added with the base signal and was taken as the received signal x(t) for the Cognitive Radio systems.

A. Energy Detection

Fig. 1 shows the implementation of detection of primary users in cognitive systems by energy detection method. The Power Spectral Density of the received signal was plotted and from it the peak frequencies that are above the threshold (λ) were found out. Probability of detection was evaluated and plotted for different Signal to Noise ratio in dB.

![Fig 1. Energy detection technique](image)

B. Matched Filter

Fig. 2 shows the implementation of detection of primary users in cognitive systems by matched filtering. The a priori information of the shape and frequency of the primary signal should be available at the receiver. The received signal is passed through a filter whose impulse response is same as the shape of the transmitted signal. The output was compared with the stored signal. Probability of detection was calculated and plotted for different Signal to Noise ratio in dB.

![Fig 2. Matched filter detection technique](image)

C. Cyclostationary feature detection

Fig. 3 shows the implementation of detection of primary users in cognitive systems by cyclostationary feature detection. The Power Spectral Density of the received signal was correlated with itself. The peaks and the frequency of the peaks were calculated. Probability of detection was evaluated and plotted for different Signal to Noise ratio in dB.

![Fig 3. Cyclostationary feature detection technique](image)
IV. RESULTS

Fig. 4 shows the comparison of spectrum sensing techniques by Matched Filtering, Energy Detection, and Spectral Correlation. It is evident that though Spectral correlation is robust in low SNR, it can have high computation cost whereas matched filter can be an optimal solution if a priori information of the primary user is known. On the other hand if primary signals are completely ‘random’ then energy detection can be the best option.

The first trade off can be the a priori information on the primary user and the performance. Obviously, the a priori information can greatly improve the performance as shown in Fig. 4 for matched filtering and spectral correlation. On the other hand, if the primary users are more ‘random’ in nature, the approaches without requiring the prior information, such as the energy detector would fit. But the performance can be low in low SNR region as shown in Fig. 4.

The second trade off can be complexity. The cognitive radio devices for the customer should be of low cost. Thus the choice of the spectrum sensing approach can be determined by the specific scenario in consideration. This paper on spectrum sensing thus far was mainly focused on individual users. An important venue for further research can be “cooperative spectrum sensing” [6] which requires a flexible policy, regulating the dynamic access to spectrum based on the behavior and capabilities of a cognitive radio network as a whole rather than individual users.

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REFERENCES