Study and Analysis of Spectrum Sensing Techniques and Implementation of Matched Filters in Cognitive Radio Systems

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ABSTRACT - Spectrum sensing is an essential enabling functionality for cognitive radio networks to detect spectrum holes and opportunistically use the under-utilized frequency bands without causing harmful interference to legacy networks. This paper introduces a novel wideband spectrum sensing technique, called multiband joint detection, which jointly detects the signal energy levels over multiple frequency bands rather than consider one band at a time. This radio link may offer simple line-of-sight or multipath propagation of communication signal depending on channel condition and channel type. The proposed strategy is efficient in improving the dynamic spectrum utilization and reducing interference to the primary users and also enlightens the implementation and analysis through simulation of Matched filtering. The spectrum sensing problem is formulated as a class of optimization problems in interference limited cognitive radio networks. By exploiting the hidden convexity in the seemingly non-convex problem formulations, optimal solutions for multiband joint detection are obtained under practical conditions. Simulation results show that the proposed spectrum sensing schemes can considerably improve the system performance. This paper establishes important principles for the design of wideband spectrum sensing algorithms in cognitive radio networks.

Keywords: Cognitive, Spectrum sensing, Energy detection, Matched filtering, Cyclostationary detection, Cooperative sensing

I. INTRODUCTION

The exponential and unpredicted growth in wireless communication demands additional bandwidth or efficient bandwidth utilization of existing spectra. Cognitive radio (CR) has emerged as a leading technology because it can intelligently sense an unused spectrum without creating any harmful interference to authorized users. Spectrum sensing is an essential functionality of cognitive radios since the devices need to reliably detect weak primary signals of possibly-unknown types [20]. In general, spectrum sensing techniques can be classified into three categories: energy detection [21], matched filter coherent detection [22], and cyclostationary feature detection [23]. Since non-coherent energy detection is simple and is able to locate spectrum Occupancy information quickly, we will adopt it as a building block for constructing the proposed wideband spectrum sensing scheme. There are previous studies on spectrum sensing in cognitive radio networks with focus on cooperation among multiple cognitive radios [20] [24] [25] via distributed detection approaches [26] [27]. However, they are limited to the detection of signals on a single frequency band. In [28], two decision-combining approaches were studied: hard decision with the AND logic operation and soft decision using the likelihood ratio test [26]. It was shown that the soft decision combination of spectrum sensing results yields gains over hard decision combining. In [29], the authors exploited the fact that summing signals from two secondary users can increase the signal-to-noise ratio (SNR) and detection reliability if the signals are correlated. In [30], a generalized likelihood ratio test for detecting the presence of cyclostationarity over multiple cyclic frequencies was proposed and evaluated through Monte Carlo simulations. Cognitive radio network is not introduced as a replacement but complement to the existing wireless communication networks. It can operate in licensed frequency bands in order to improve quality of service (QoS) to its users. Spectrum utilization and efficiency can be improved by allowing secondary or unlicensed users to access spectrum hole, unoccupied by a primary user (PU), at the right location and time. Spectrum sensing is a crucial step in cognitive radio. Therefore for the system to provide good quality of services to the secondary users, they need to have valuable and trusted
sensing techniques in order to sense idle spectrum holes in the network. Different from conventional wireless radios, CR is able to monitor and analyse existing spectrum usage with determination of its operating parameters, to effectively adapt varying radio environment. CR users are allowed to utilize licensed spectrum bands opportunistically, as long as they do not cause any unacceptable interference with licensed users. Such flexibility alleviates the crowding and congestion issue in particular spectrum bands and greatly enhances the efficiency of spectrum utilization. Consequently, CRSpectrum sensing is an essential functionality of cognitive radios since the devices need to reliably detect weak primary signals of possibly-unknown types [1]. In general, spectrum sensing techniques can be classified into three categories: energy detection [2], matched filter coherent detection [3], and cyclostationary feature detection [4]. Since non-coherent energy detection is simple and is able to locate spectrum occupancy information quickly, we will adopt it as a building block for constructing the proposed wideband spectrum sensing scheme. There are previous studies on spectrum sensing in cognitive radio networks with focus on cooperation among multiple cognitive radios [1] [5] [6] via distributed detection approaches [7] [8]. However, they are limited to the detection of signals on a single frequency band. In [9], two decision-combining approaches were studied: hard decision with the AND logic operation and soft decision using the likelihood ratio test [7]. It was shown that the soft decision combination of spectrum sensing results yields gains over hard decision combining. In [10], the authors exploited the fact that summing signals from two secondary users can increase the signal-to-noise ratio (SNR) and detection reliability if the signals are correlated. In [11], a generalized likelihood ratio test for detecting the presence of cyclostationarity over multiple cyclic frequencies was proposed and evaluated through Monte Carlo simulations. technology has gained increasing attention and highlighted by both standards and regulatory bodies [1], [7], [8], [17]. CR can smartly sense and adapt idle spectrum in rapidly changing environment, using its transmitting parameters such as modulation, frequency, frame format etc. CR is being recognized as an intelligent technology to adapt operating parameters from changing environment rapidly and enormously [16]. The main challenges with cognitive radios are that it should not interfere with the licensed users and should release the band when required. The objective of this paper is to implement and simulate Matched filtering. Energy detection and Cyclostationary feature detection cognitive radio spectrum sensing techniques as well as analyse the simulation results. This paper is organized as follows: Section II defines Matched filtering spectrum sensing technique. Section III presents Energy detection spectrum sensing techniques. Cyclostationary feature detection spectrum sensing technique is explained in section IV. Propagation channels are defined in section V. Decision accuracy also enlightens in section VI. Simulation results are shown in section VII with their respective inferences. Section VIII concludes this paper. In this paper, we introduce the multiband joint detection framework for wideband spectrum sensing in individual cognitive radios. Within this framework, we jointly optimize a bank of multiple narrowband detectors in order to improve the opportunistic throughput capacity of cognitive radios and reduce their interference to the primary communication systems. In particular, we formulate wideband spectrum sensing into a class of optimization problems. The objective is to maximize the opportunistic throughput in an interference limited cognitive radio network. By exploiting the hidden convexity of the seemingly non-convex problems, we show that the optimization problems can be reformulated into convex programs under practical conditions. The multiband joint detection strategy allows cognitive radios to efficiently take advantage of the unused frequency bands and limit the resulting interference.

**II. SYSTEM MODELS**

A. Wideband Spectrum Sensing

Consider a primary communication system (e.g., a multicarrier modulation based system) over a wideband channel that’s divided into K non-overlapping narrowband subchannels in a particular geographical region and time, some of the K sub channels might not be utilized by the primary user and are available for opportunistic spectrum access. Multiuser orthogonal frequency division multiplexing (OFDM) is an ideal candidate for such a scenario since it makes the sub band manipulation easy and flexible. We model the occupancy detection problem on subchannel k as one of choosing between H0,k (“0”), which represents the absence of primary signals, and H1,k (“1”), which represent the presence of primary signals. An illustrative example where only some of the K bands are occupied by primary users depicted in Fig.1. The underlying hypothesis vector is binary representation of the...
subchannels that are allowed for prohibited from opportunistic spectrum access.

B. Received Signal

Consider a multi-path fading environment, where \( h(l), l = 0, 1, \ldots, L-1 \) denotes the discrete-time channel impulse response between the primary transmitter and cognitive Radioreceiver, with \( L \) as the number of resolvable paths. where \( s(n) \) is the primary transmitted signal at time \( n \) (after the cyclic prefix has been removed) and \( v(n) \) is additive complex white Gaussian noise with zero mean and variance \( \sigma^2 \). i.e., \( v(n) \sim \text{CN}(0, \sigma^2) \) In a multi-path fading environment, the wideband channel exhibits frequency-selective features [17] [18] [19].

We assume that the channel is slowly varying such that the channel frequency responses \( \{H_k\} \) remain constant during a detection interval. In the frequency domain, the received signal at each sub-channel can be estimated by first computing its discrete Fourier transform (DFT). Without loss of generality, we assume that the transmitted signal \( S_k \), the channel gain \( H_k \), and the additive noise \( V_k \) are independent of each other.

III. MULTIBAND JOINT DETECTION

In this section, we present the multiband joint detection framework for wideband spectrum sensing, as illustrated in Fig. 2. The design objective is to find the optimal threshold vector \( \gamma = [\gamma_0, \gamma_1, \ldots, \gamma_{K-1}]^T \) so that the cognitive radio system can make efficient use of the unoccupied spectral segments without causing harmful interference to the primary users. Consider a cognitive radio sensing the \( K \) narrowband sub channels in order to opportunistically utilize the unused ones for transmission. Let \( T_k \) denote the throughput achievable over the \( k \)th subchannel if used by cognitive radios, and \( r = [r_0, r_1, \ldots, r_{K-1}]^T \). Since \( 1-P_f(k) \) measures the opportunistic spectrum utilization of subchannel \( k \), we define the aggregate opportunistic throughput capacity as

\[
R(\gamma) = r^T [1 - P_f(\gamma)]
\]

Which is a function of the threshold vector \( \gamma \). Due to the inherent trade-off between \( P_f(k) \) and \( P_m(k) \), maximizing the sum rate \( R(\gamma) \) will result in large \( P_m(\gamma) \), hence causing harmful interference to primary users. Intuitively, we could make some observations on the multiband joint detection. First, the subchannel with a higher opportunistic rate \( T_k \) should have a higher threshold \( \gamma_k \) (i.e., a smaller probability of false alarm) so that it can be highly used by cognitive radios. Second, the subchannel that carries a higher priority primary user should have a lower threshold \( \gamma_k \) (i.e., a smaller probability of miss) in order to prevent harmful interference by secondary users. Third, a little compromise on those subchannels carrying less important primary users might boost the aggregate rate considerably. Thus, in the determination of the optimal threshold vector, it is necessary to strike a balance among the channel condition, the opportunistic throughput, and the relative priority of each subchannel by using matched filters.

MATCHED FILTERING

The optimal way for spectrum sensing in cognitive radio is Matched filtering technique. It is popular due to its very accurate detection probability and less detection time, which maximizes SNR. Matched Filtering needs short time to achieve a certain probability of false alarm or probability of missed-detection [2, 7]. Matched filter performs coherent detection of primary signal user and works as a linear filter [3, 2, 1, 5]. Output of the filter results the desired useful signal, while attenuating noise signals. To filter the desired signal, it requires a prior knowledge of every primary user signal, which needs a dedicated receiver for every type of primary user signal. However, it increases implementation complexity and power consumption. To detect the signals it also requires execution of various receiver algorithms at sensing unit [3, 2, 1, 6, 7, 8]. Primary user information e.g., modulation type and order, pulse shaping, packet format bandwidth and operating frequency might be pre-stored in CR memory. In matched filter operation, received signal is convolved with the filter impulse response which is time shifted and mirror version of reference signal, this terminology approaches to the correlation of signals [3, 2, 5, 8]. Optimal detector in stationary Gaussian noise used as matched filter, when secondary user has knowledge about information of primary user signal [8, 10]. Matched filter performs poorly in case of incomplete or inaccurate information [8, 10]. The operation of matched filter detection is expressed as [3, 2, 1, 8] fig 2 shows block diagram of Matched filtering process, which consists of a band pass filter to allow specific band spectrum. Linear matched filter performs filtering of received signal. Output of signal is defined by hypothesis H0 and H1.

ENERGY DETECTION

Simplicity and ease of applicability of energy detection technique represents it as the most preferred approach for spectrum sensing in cognitive radio technology [16]. It is very simple and non co-herent detection based sensing technique of CR [6]. The detection and comparison of signal energy introduces principle of this
Technique. Energy of desired spectrum calculated in this technique and compares it with threshold energy level [16]. If the signal energy lies above the threshold energy level, the respective frequency band seems to be busy. Otherwise the frequency band is supposed to be idle and could be accessed by CR users (secondary users) [4, 13, 16]. It offers low computational and implementation cost and does not require the prior knowledge about the structure or format of the primary user signal [16]. The threshold used for primary user signal detection is highly susceptible to changing noise levels. Moreover, presence of any undesired band possessing equal energy level could confuse the energy detector. Other than this, energy detector is not useful for direct sequence, frequency hopping signals and spread spectrum signals. Energy detection technique requires long time to achieve desired performance level [4, 6, 11, 13, 16]. These factors limit the performance of this technique in comparison to matched filtering and cyclostationary feature detection techniques. Spectrum sensing is a binary hypothesis problem described in below equation:

\[ X(t) = \begin{cases} n(t) & H_0, \\ s(t) + n(t) & H_1 \end{cases} \]

where \( s(t) \) represents primary user signal while noise signal received with primary user signal is denoted by \( n(t) \). \( X(t) \) define total signal received. \( H_0 \) represents presence of noise only, while \( H_1 \) represents the presence of primary user signal [16, 17].

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**CYCLOSTATIONARY FEATURE DETECTION**

Cyclostationary feature detection introduces one of the most reliable and accurate method of spectrum sensing. Signal format of modulated primary users signals are associated with sine wave carriers, pulse trains, repeating sequences, spreading, hoping sequences, or cyclic prefixes. It exploits periodicity as well as mean and autocorrelation of PU signals. Cyclostationary feature of primary user signal is characterized by this periodicity, which is used for detection of the signal in random radio environment. Receiver exploits cyclic features of primary user signal and performs signal detection using previously stored cyclic features of signal. Frequency and phase synchronization of signal is not required at the receiver end but prior knowledge of primary user signal is necessary. This technique performs better than energy detection method in low SNR regions. Also, noise uncertainties do not affect its performance. However, this complex two dimensional technique requires long observation time, high sampling rate and higher computational complexity, which may
cause sampling time error [3, 2, 1, 4, 5, 6, 7, 12, 13]. As stationary random signals are based on autocorrelation functions and power spectral density, cyclostationary signal exhibits correlation between widely separated spectral components due to spectral redundancy caused by periodicity [6].

The received signal is assumed to be of following simple form

\[ X(n) = s(n) + w(n) \]

The cyclic spectral density (CSD) function of a received signal can be calculated as

\[ S(f, \alpha) = \sum_{\tau = -\infty}^{\infty} \langle R_x^c (\tau) \rangle e^{-j2\pi \frac{\tau f}{T}} \]

Where

\[ \langle R_x^c (\tau) \rangle = E \left[ y(n + \tau) y(n - \tau) e^{j2\pi \alpha n} \right] \]

is the cyclic autocorrelation function (CAF) and is the cyclic frequency. When the cyclic frequency is equal to the fundamental frequency of the transmitted signal \( x(n) \), then the CSD function exhibits its maximum values [2, 1, 6, 7]. Cyclic frequencies are used as features for identifying transmitted PU signals. It can be assumed to be known or they can be extracted [7]. Spectral correlation function is also termed as cyclic spectrum [1, 7]. Signal analysis in cyclic spectrum domain preserves phase and frequency information related to timing parameters in modulated signals. As a result, overlapping features in the power spectrum density are non-overlapping features in the cyclic spectrum [6].

IV. SIMULATION RESULTS

Implementation and simulation of cognitive radio spectrum sensing techniques give various important results, which show their performance over varying SNR as well as over AWGN, Rician fading and Rayleigh fading channels. Sinusoidal carrier signals in frequency range of 20MHz to 40MHz is defined for each of 20 users and calculate signal power and noise power. Modulate the signal using BPSK modulation before passing it through channel. At output of channel these modulated signals are contained noise signal also. So the spectrum sensing technique is applied on noise affected signals. Decision accuracy of each technique is calculated by assuming 70% occupancy of sensed frequency band.

4.1 Matched Filtering

Figure 5 shows sensing result of Matched filtering technique. This plot represents status of all 20 users (primary users), either these are present or not at their respective frequency band. Figure 6 represents decision accuracy of matched filtering technique over AWGN, Rician fading channel and Rayleigh fading channel with respect to varying signal to noise ratio. Plot indicates decision accuracy of matched filtering technique increases with increase in SNR. This technique performs better over Rician fading channel while the performance over AWGN and Rayleigh fading channel also close to Rician fading channel [25].
V. CONCLUSION

It is a novel approach to fulfill increasing demand of band-width for effective and healthy communication. Varying SNR in radio environment may affect performance of spectrum sensing techniques. Spectrum sensing is a multifaceted problem demanding coordinated efforts of the regulatory and technical sides. In this paper a comparative analysis of spectrum sensing capability of matched filtering, Energy detection and cyclostationary feature detection technique was carried out in terms of decision accuracy vs SNR under varying channel conditions including AWGN, Rician fading, Rayleigh fading, and useful inferences were drawn. We have proposed a multiband joint detection approach for wideband spectrum sensing in cognitive radionetworks. The basic strategy is to take into account the detection of primary users across a bank of narrowband subchannels jointly rather than to consider only one single band at a time. We have formulated the joint detection problem into a class of Optimization problems to improve the spectral efficiency and reduce the interference[26]

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