Study Of Spectrum Sensing Techniques For OFDM Based Cognitive Radio

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Abstract: Nowadays OFDM (Orthogonal Frequency Division Multiplexing) techniques are adopted by many existing or progressing wireless communication standards. OFDM’s sensing and spectrum shaping capabilities together with its flexibility and adaptivity make it the best transmission technology for CR system. Spectrum sensing helps to detect the spectrum holes (unutilized bands of the spectrum) providing high spectral resolution capability. Thus, a robust spectrum sensing algorithm for OFDM modulated signals is highly decide to implement CR when the primary signal uses OFDM modulation. Motivated by this demand, a Time-Domain Symbol Cross-correlation based spectrum sensing algorithm (TDSC method) is presented in this paper. The algorithm makes use of the property that the mean of the TDSC of two OFDM symbols is not zero if they have embedded the same frequency-domain pilot tones. We propose a new decision statistic for the signal detection based on the special feature – Cyclic Prefix embedded in OFDM signal. Further, in this paper we used to control the Transmit Power for cognitive radio. Different spectrum sensing techniques for OFDM based cognitive radio are discussed in this paper.

Keywords: Cognitive Radio, OFDM, Spectrum Sensing, Energy Detection, Matched Filter, Cyclostationary Feature Detection.

I. Introduction

The cognitive radio concept dates back to 1998 when the idea was first conceived by Sir Joseph Mitola III at the Royal Institute Of Technology in Stockholm. The major driving factor behind was the ever increasing requirement for the radio spectrum. There was an unusual drive for improved communication speeds. The only way to provide communication flexibility was by efficiently utilizing the radio spectrum. Cognitive Radio turns out to be a solution to the spectral crowding problem by introducing the opportunistic usage of frequency bands. These frequency bands must not be occupied by licensed users. One most important component of a cognitive radio is its ability to measure, sense, learn, and be aware of the parameters related to the radio channel characteristics, the availability of radio spectrum as well as power, the user requirements and their applications, and also other operating restrictions. In cognitive radio terminology, primary user (PU) can be defined as the user who possesses higher priority on the usage of any specific part of the spectrum. Secondary user is the one with much lower priority. The secondary user gets access to this spectrum in such a way that it does not cause any sort of interference to the already existing primary user. Therefore, a secondary user should have cognitive radio capabilities, such as sensing the spectrum reliably so as to check whether the band of the spectrum is being used by any primary user and to change its own radio parameters in order to exploit the unused band of the spectrum [2]. Spectrum sensing can be described as an art of performing measurements on a part of the radio spectrum and forming a decision related to the spectrum usage based upon the earlier measured data. Now a day, the service providers face a situation in which they require a larger amount of spectrum to satisfy the increasing quality of service (QoS) requirements of the users. This is the reason for the increased interest in unlicensed spectrum access, and spectrum sensing is an important enabler for this. Spectrum sensing is to detect the presence (or absence) of a primary user [1,3]. For CR to achieve this objective, the CR needs to be highly flexible and adaptable. A special case of multicarrier transmission known as orthogonal frequency division multiplexing (OFDM) is one of the most widely used technologies in current wireless communications systems.

II. OFDM-BASED CR

OFDM is a multicarrier modulation technique that can overcome many problems that arise with high bit rate communications, the biggest of which is time dispersion. The databearing symbol stream is split into several lower rate streams and these streams are transmitted on different carriers. Since this splitting increases the symbol duration by the number of orthogonally overlapping carriers (subcarriers), multipath echoes affect only a small portion of the neighboring symbols. Remaining inter-symbol interference (ISI) is removed by extending the OFDM symbol with a cyclic prefix (CP). Using this method, OFDM reduces the dispersion effect of multipath channels encountered with high data rates and reduces the need for complex equalizers. Other advantages of OFDM include high spectral efficiency, robustness against narrowband interference (NBI), scalability, and easy implementation using fast Fourier transform (FFT).
Table 1: Summary of CR’s requirements and OFDM’s strength.

<table>
<thead>
<tr>
<th>CR Requirements</th>
<th>OFDM’s Strength</th>
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<tbody>
<tr>
<td>Spectrum Sensing</td>
<td>Inherent FFT operation of OFDM eases spectrum</td>
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<tr>
<td></td>
<td>Sensing in frequency domain.</td>
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<tr>
<td>Efficient spectrum</td>
<td>Waveform can easily be shaped by simply turning off</td>
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<tr>
<td>utilization</td>
<td>some subcarriers where primary users exist.</td>
</tr>
<tr>
<td>Adaptation/Scalability</td>
<td>OFDM systems can be adapted to different transmission</td>
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<tr>
<td></td>
<td>environments and available resources. Some adaptable</td>
</tr>
<tr>
<td></td>
<td>parameters are FFT size, subcarrier spacing, CP size,</td>
</tr>
<tr>
<td></td>
<td>modulation, Coding, subcarrier powers</td>
</tr>
<tr>
<td>Advanced antenna</td>
<td>Techniques such as multiple-input multiple-output</td>
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<tr>
<td>Techniques</td>
<td>(MIMO) are commonly used with OFDM mainly because of</td>
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<td></td>
<td>the reduced equalizer complexity. OFDM also supports</td>
</tr>
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<td></td>
<td>smart techniques</td>
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<tr>
<td>Multiple accessing and</td>
<td>Support for multiuser access is already inherited in</td>
</tr>
<tr>
<td>spectral allocation</td>
<td>the system design by assigning groupsof subcarriers</td>
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<td></td>
<td>to different users (i.e. orthogonal frequency division</td>
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<td></td>
<td>multiple access (OFDMA)).</td>
</tr>
</tbody>
</table>

III. OFDM Signal Generation

OFDM systems rely on orthogonal multi-carriers which are optimally spaced to carry the data. The spectrum sensing for OFDM systems in blind environment poses a greater challenge which relies on centre frequency, carrier spacing, and bandwidth estimations. Spectrum utilization techniques for OFDM systems goes one step beyond other systems as they utilize the null subcarriers (subcarriers not utilized by primary user), technique known as spectrum spooling. The QAM symbols generated are surpassed through the Inverse Fourier Transform algorithm. The FFT is necessary to compute the frequency response of the time variant function. We incorporated IFFT for our input QAM symbols which give frequency response in time domain typically giving OFDM subcarriers. The receiver computes the Fourier transform of the received signal in order to get the desired symbol period and energy levels. The nature of OFDM is that it can sustain the changes caused by environment variables like fading, interference attenuation especially at higher frequencies [9].

Figure 1. OFDM Signal Generation

OFDM Signals can cope up with severe intersymbol interference (ISI) if the guard band interval is set with respect to the signal time period and sampling rate. As the symbol stream is low-rate for OFDM signals, we can add guard bands to avoid any ISI between corresponding parallel streams [9]. A guard band also eliminates the needs of a pulse shaping filter. The cyclic prefix generator is normally used with guardbands to identify the signal and sub-carrier boundaries at the receiver while taking FFT [8, 9]. The cyclic prefix generator appends the end bits of OFDM signal in guard bands and transmits along, thus providing a stream of end points alongwith the actual signal, so that the receiver can detect the actual length of the symbols received. OFDM signal in mathematical form:

\[
S(t) = \text{Re} \left\{ \sum_{i=-N_s/2}^{N_s-1} d_i e^{j2\pi \left( \frac{i+\frac{1}{2}}{T} \right) (t-t_s)} \right\}
\]

Where T is the OFDM symbol duration, \(t_s\) being the starting time of symbol, \(N_s\) is no. of subcarriers & \(d_i\) is the complex symbol for QAM modulation. The signal generated is corrupted by AWGN channel [11]. Therefore with our assumption the received signal towards the receiver takes a very simple form of:

\[ x(t) = S(t) + w(t) \]

where x(t) is the signal to be detected and w(t) is the additive white Gaussian noise.

IV. Spectrum Sensing Techniques

Spectrum sensing is the process of a cognitive radio sensing the channel and determining if a primary user is present, detecting the spectrum holes. In this paper we discuss about the techniques used in spectrum sensing. Three different signal processing techniques that are used in this paper are matched filter, energy detector and cyclostationarity feature detection. Consider the hypothesis test for signal detection:

\[
H_0: Y[n] = W[n] \quad n=0,1,\ldots,N-1 \\
H_1: Y[n] = X[n] + W[n] \quad n=0,1,\ldots,N-1 \\
H_0: \text{Primary user is absent.} \\
H_1: \text{Primary user is present.}
\]

Here it is assumed that \(W[n]\) are the samples of additive white Gaussian noise with spectral density \(\sigma^2\). \(e^{j2\pi f_c n}\) is the input sample sequence.
A. Energy Detection

Energy detector is also known as radiometry and it is most common method of spectrum sensing because of its low computational and implementation complexities. Moreover, the cognitive user’s receivers do not need any knowledge of the primary user’s signal. The signal is detected by comparing the output of energy detector with threshold which depends on noise floor [4].

\[
T(Y) = \sum_{n=0}^{N-1} Y[n]^2 \geq H_0 Y
\]

\[
N = 2 \left[ (Q^{-1} (P_1) - Q^{-1} (P_0) \right) (\text{snr})^{-1} - (P_0) \right]^2
= O(\text{SNR})^2
\]

Then number of samples required to optimally detect the incoming signal is \(O(1/\text{SNR}^2)\) [5, 7]. The problems in using energy detector is the threshold that is used for detecting primary signals is prone to unknown changes in noise levels. If the noise levels are changed adaptively, then the presence of interference can cause poor detection of signal energy. If the channel is nonflat, then it is possible to set the threshold with respect to the noise levels caused by its frequency selectivity. Since the energy detector is only concerned with the energy of the incoming signal, it does not differentiate between noise and interference. In context to cognitive radios interference and noise should be treated differently because of the presence of unlicensed and licensed users. Detection energy detector becomes prone to false detection. The hypothesis model for transmitter detection can be defined as:

\[
x(t) = \begin{cases} n(t)H_0 & \text{if } H_1 \\
 h \ast s(t) + n(t) & \text{if } H_0
\end{cases}
\]

Here \(x(t)\) is the signal received by the unlicensed user, \(s(t)\) is the signal transmitted by the licensed transmitter, \(n(t)\) is the noise introduced by AWGN and \(d\) is the channel gain. \(H_0\) is the null hypothesis where there is no primary signal and \(H_1\) indicates the presence of a primary signal [8]. The probability of detection \(P_d\) and false alarm \(P_f\) are given as follows [9].

\[
P_d = P \left\{ Y > \frac{\lambda}{H_1} \right\} = Q_m (\sqrt{2} Y, \sqrt{1})
\]

\[
P_f = P \left\{ Y > \frac{\lambda}{H_0} \right\} = r(m, \frac{\lambda}{2})/r(m)
\]

In these equations, \(\lambda\) is the threshold and \(Q_m(a, b)\) is a generalized Marcum Q-function, \(a\) and \(b\) are nonnegative real numbers, and \(m\) is a positive integer. A low detection probability will result in absence of primary signal and a high threshold would result in inefficient spectrum utilization. The drawbacks of this system are it has poor performance in low SNR regimes [9].

I. Sensing OFDM Systems Under Frequency-Selective Fading Channels

As shown in Fig. 2, OFDM signals have a CP, which is a special feature differentiating them from other signals that could be exploited for signal detection. By utilizing the CP, we are presenting a new detection scheme for OFDM signals.

![Fig. 2. Typical OFDM symbol structure](image)

A typical OFDM signal received, after passing through a multipath fading channel, at a sensing device is illustrated in Fig. 3 (three paths are drawn for the illustration purpose). The two arrows connected indicate two samples of signals with a sampling time distance of one useful OFDM symbol duration (the symbol duration before adding a CP) or \(M\). It can be seen and will be proved later that the two samples may exhibit strong correlation even in a multipath environment when the first sample falls within the CP duration for any one of the paths, due to the fact that the transmitted CP is a copy of the part of the signal with sampling time distance \(M\). Exploiting the correlation, we examine the following hypotheses:

\[
H_0 : \quad \zeta = \sum_{d=1}^{W} z_d = \sum_{d=1}^{W} \frac{r_{a}n_{a} + r_{b}n_{b}}{E[|r_{d}|^2]}
\]

\[
H_1 : \quad \zeta = \sum_{d=1}^{W} z_d = \sum_{d=1}^{W} \frac{r_{a}n_{a} + r_{b}n_{b}}{E[|r_{d}|^2]}
\]

Where \(z_d, r_{a}n_{a} + r_{b}n_{b}/E[|r_{d}|^2]\). "a" stands for the Hermitian operation, and the summation is over the observation window \(W\), which can be single continuous time interval or multiple discontinuous subwindows.
II. Spectrum Sensing for OFDM Systems Employing Pilot Tones and Application to DVB-T OFDM

Statistical Development Of The Correlation Of Two OFDM Symbols

Under the assumption that L, the length of the Cyclic Prefix (CP), is longer than the length of the time-invariant channel, the nth sample of the lth OFDM symbol can be modeled as

\[ x_l[n] = e^{j(2\pi f_0 + \theta_l)} \frac{1}{N} \sum_{k=0}^{N-1} H[k] X[k] e^{j2\pi kn/N} + w_l[n] \]

Where \( f_0 \) is the carrier frequency offset normalized to the subcarrier spacing. The phase \( \theta_l = \frac{2\pi f_0 L}{N} + \theta_c \) is the initial phase of the lth OFDM symbol where \( M = N + L \) is the length of an OFDM symbol. The parameter N is the number of subcarriers, and \( X[k] \) which is taken from a finite complex alphabet constellation denotes the data symbols at the kth subcarrier of the lth OFDM symbol.

C. Cyclostationary Feature Detection

An alternative method for detection of primary signals is Cyclostationary Feature Detection in which modulated signals are coupled with new carriers, pulses trains, repeated spreading, hopping sequences, or cyclic prefixes. This results in built-in incoherence. The modulated signals are characterized as cyclostationary because the mean and autocorrelation exhibit cyclostationarity. This cyclostationarity is introduced in the signal format at the receiver. The signal is a complex additive white Gaussian noise (AWGN) process. The noise is the complex channel gain of the kth subcarrier and \( w_l[n] \) is a sample of a complex additive white Gaussian noise (AWGN) process. We will assume that \( w_l[n] \) is a circularly symmetric complex Gaussian random variable which has zero mean and a variance of \( \sigma_w^2 \). Most of the existing standards which adopt OFDM modulation [8][9][10] allocate pilot symbols in the frequency domain and these pilot symbols are called pilot tones. Let \( P_a = 0, 1, \ldots, A - 1 \), denote the sets of all possible pilot tone positions for the transmitted OFDM symbols. Assume that \( P_a \) is the set of pilot tone positions of the lth OFDM symbol and \( X[k] = P_a[k] \) for \( k \in P_a \).

Here, we should note that the pilot symbols \( P_a[k] \) are predefined and have the same amplitude. For most cases, \( P_a[k] \) is a fixed constant and in some cases they change sign. Assume that the lth and mth OFDM symbols have the same pilot tone positions and define

\[ R(l,m) = \frac{1}{N} \sum_{n=0}^{N-1} x_l[n] x_m^*[n] \]

which is the Time-Domain Symbol Cross-correlation (TDSC) function of two OFDM symbols.

B. Matched Filter

It is a linear filter which maximizes the signal-to-noise ratio. The main advantage of this filter is that it requires less time to achieve high processing gain because of the coherence [5]. If \( X[n] \) is completely known to the receiver then the optimal detector for this case is [10]:

\[ T(Y) = \sum_{n=0}^{N-1} Y[n] X[n] H_0^* \]

Here \( \gamma \) is the detection threshold, then the number of samples required for optimal detection are

\[ N = \left[ Q^{-1}(P_d) - Q^{-1}(P_f) \right]^2 \text{snr}^{-1} \]

Where \( P_d \) and \( P_f \) are the probabilities of detection and false detection respectively. Thus the number of samples required for optimal detection is \( O(1/\text{SNR}) \). However, a matched filter effectively requires demodulation of the signal of the licensed user, the primary user. This means that cognitive radio has an a priori knowledge of primary user signal at both PHY and MAC layers, e.g., modulation type and order, pulse shaping, packet format. These data can be pre-stored in cognitive radio memory, but for performing demodulation it has to perform timing and carrier synchronization, even channel equalization. This is still possible since most primary users have pilots, preambles, synchronization words or spreading codes that can be used for synchronization [8].

Figure 2 Implementation of Cyclostationary Feature Detector

Because of the inherent spectral redundancy signal
selectivity becomes possible. Analysis of signal in this domain retains its phase and frequency information unrelated to timing parameters of modulated signals. Due to the overlapping features in power spectral density, a non-integer overlap of features in the cyclic spectrum. Hence different types of modulated signals that have identical power spectral density can be discriminated during noise. However, it is computationally complex and requires significant large observation time. For more efficient detection, the enhanced feature detection scheme is combined with cyclic spectrum analysis and pattern recognition based on neural networks is proposed in [7].

D. Comparison between different spectrum sensing techniques:

<table>
<thead>
<tr>
<th>Detection Method</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Detector</td>
<td>No need of primary user information, low computation &amp; less expensive</td>
<td>Performance poor at low SNR, Lead to false detection.</td>
</tr>
<tr>
<td>Matched Filter</td>
<td>Require less time to achieve high processing gain.</td>
<td>Prior knowledge of primary user required, need coherent detection, require accurate synchronization.</td>
</tr>
<tr>
<td>Cyclostationary</td>
<td>Perform well at low SNR condition &amp; uncertain noise power</td>
<td>Computationally complex, Require large observation time.</td>
</tr>
</tbody>
</table>

V. Some other techniques

A. Covariance Detection

This method determines if a primary user is present from the covariance matrix of the received signal. It uses the property that the off diagonal elements of the covariance matrix are non-zero when a primary user is present and zero otherwise [12].

B. Wavelet Detection

For signal detection over wideband channels, the wavelet approach offers advantages in terms of both implementation cost and flexibility in adapting to the dynamic spectrum as opposed to conventional use of multiple narrowband pass filters (BPF). Unlike the Fourier transform, using sines and cosines as basic functions, the wavelet transforms use irregularly shaped wavelets as basic functions and thus offer better tools to represent sharp changes and local features. In order to identify the locations of vacant frequency bands, the entire wide-band is modeled as a train of consecutive frequency sub bands where the power spectral characteristic is smooth within each sub band but changes abruptly on the border of two neighboring sub bands. By employing a wavelet transform of the power spectral density (PSD) of the observed signal, the singularities of the PSD can be located and thus the vacant frequency bands can be found. One critical challenge of implementing the wavelet approach in practice is the high sampling rates for characterizing the large bandwidth.

C. Eigen value based Detection

Eigenvalue-based Detection (EBD) has been introduced as an efficient technique to perform spectrum sensing in Cognitive Radio (CR). Using the EDB approach, the secondary receiver is able to infer the presence or the absence of a primary signal based on the largest and the smallest eigenvalue of the received signal’s covariance matrix. This technique requires a cooperative detection setting, which may be accomplished by multiple antennas or cooperation among different users. The main advantage offered by EDB is its robustness to the problem of noise uncertainty, which affects all the previously proposed detection schemes including the widely adopted Energy Detection (ED).

VI. Conclusions

The growing demand of wireless applications has put a lot of constraints on the usage of available radio spectrum which is limited and precious resource. In wireless communication system spectrum is a very important resource. In cognitive radio OFDM based systems, reliable spectrum sensing techniques are required in order to avoid interference to the primary users. In this paper, different spectrum sensing techniques are discussed with their advantages and disadvantages.

REFERENCES


