ROC ANALYSIS OF SPECTRUM SENSING TECHNIQUES IN COGNITIVE RADIO FOR OFDM SYSTEM

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Abstract - Wireless technology is embedded in our daily routine – laptops, cell phones, sensors – all are wireless devices and use a finite amount of radio spectrum. As the number of devices increases, they compete for bandwidth and the service level provided to them is degraded. Moreover, traditional fixed spectrum allocation policy can no longer meet the needs and services of the wireless users. According to Federal Communications Commission (FCC), temporal and geographical variations in the utilization of the assigned spectrum range from 15% to 85% in current spectrum allocation policies. So, we need to find out ways to allow wireless devices to efficiently share the em waves. Cognitive Radio (Dynamic Spectrum Access) has been proposed as a potential solution for spectrum inefficiency problems.

1) To study and analyze the performance of energy detection based spectrum sensing technique and cyclic prefix based spectrum sensing technique using ROC (Receiver Operating characteristics) curves.
2) To implement energy detection and cyclic prefix based spectrum sensing techniques on wireless channels in OFDM system.

Key Words: Cognitive Radio, multi-carrier transmission, Orthogonal Frequency Division Multiplexing

1. INTRODUCTION -

COGNITIVE radio is a promising solution to the problem of “spectrum scarcity” caused by the rapid development of wireless services [1]. It reuses the licensed frequency bands that are not occupied by the licensed users at some specific times in some specific locations [2]. Most cognitive radios have two important functions: spectrum sensing that detects whether the licensed band is free and data transmission that transmits cognitive radio data if the licensed band is free. In the proposed IEEE 802.22 standard[3], These two functions are performed sequentially in each frame that is divided into two period.

Figure: 1 Cognitive radio’s main functions

Consider a radio which autonomously detects and exploits empty spectrum to increase your file transfer rate. Suppose this same radio could remember the locations where your calls tend to drop and arrange for your call to be serviced by a different carrier for those locations. CRT (Cognitive Radio Technologies) can help your products

- Automatically detect and exploit unused spectrum
- Automatically detect and interoperate with varying network standards
- Improve performance (see our DFS article about how to achieve a 19 dB reduction in interference.

Important applications of CR:

1) Improving spectrum utilization & efficiency.
2) Multimedia wireless networking
3) Improving link reliability.
4) Less expensive radios.
5) Advanced network topologies.
6) Enhancing SDR techniques.
7) Automated radio resource management
2. Multi-Carrier Transmission:

The principle of multi-carrier transmission is to convert a serial high-rate data stream on to multiple parallel low-rate sub-streams. Each sub-stream is modulated on another sub-carrier. Since the symbol rate on each sub-carrier is much less than the initial serial data symbol rate, the effects of delay spread, i.e., ISI, significantly decrease, reducing the complexity of the equalizer. OFDM is a low-complex technique to efficiently modulate multiple sub-carriers by using digital signal processing [4][5][6][7][8].

An example of multi-carrier modulation with four sub-channels \( N_c = 4 \) is depicted in Figure 1. Note that the three-dimensional time/frequency/power density representation is used to illustrate the principle of various multi-carrier and multi-carrier spread spectrum systems. A cuboid indicates the three-dimensional time/frequency/power density range of the signal, in which most of the signal energy is located and does not make any statement about the pulse or spectrum shaping.

3. OFDM (Orthogonal Frequency Division Multiplexing): Block diagram

A communication system with multi-carrier modulation transmits \( N_c \) complex-valued source symbols \( S_n, n = 0, \ldots, N_c - 1 \), in parallel on \( N_c \)-sub-carriers. The source symbols may, for instance, be obtained after source and channel coding, interleaving, and symbol mapping. The source symbol duration \( T_d \) of the serial data symbols results after serial to-parallel conversion in the OFDM symbol duration

\[
T_s = N_c T_d.
\]

The principle of OFDM is to modulate the \( N_c \)-sub-streams on sub-carriers with a spacing \( F_s = 1/T_s \) in order to achieve orthogonality between the signals on the \( N_c \)-sub-carriers, presuming a rectangular pulse shaping. The \( N_c \)-parallel modulated source symbols \( S_n, n = 0, \ldots, N_c - 1 \), are referred to as an OFDM symbol. The complex envelope of an OFDM symbol with rectangular pulse shaping has the form:

\[
\chi(t) = \sum_{n=0}^{N_c-1} S_n e^{j2\pi f_s t}, 0 \leq t < T_s.
\]
inhis figure the power density spectrum is shifted to the center frequency. The symbols $S_n$, $n = 0, \ldots, N_c - 1$, are transmitted with equal power. The dotted curve illustrates the power density spectrum of the first modulated sub-carrier and indicates the construction of the overall power density spectrum as the sum of $N_c$ individual power density spectra, each shifted by $F_S$. For large values of $N_c$, the power density spectrum becomes flatter in the normalized frequency range of $-0.5 \leq fTd \leq 0.5$ containing the $N_c$ sub-channels. Only sub-channels near the band edges contribute to the out-of-band power emission. Therefore, as $N_c$ becomes large, the power density spectrum approaches that of single-carrier modulation with ideal Nyquist filtering.

A key advantage of using OFDM is that multi-carrier modulation can be implemented in the discrete domain by using an IDFT, or a more computationally efficient IFFT. When sampling the complex envelope $x(t)$ of an OFDM symbol with rate $1/Td$ the samples are

$$x_v = \frac{1}{N_c} \sum_{n=0}^{N_c-1} S_n e^{j2\pi n/v}, v = 0, \ldots, N_c - 1.$$  \hspace{1cm} (2)

The sampled sequence $x_v, \ v = 0, \ldots, N_c - 1$, is the IDFT of the source symbol sequence $S_n$, $n = 0, \ldots, N_c - 1$. The block diagram of a multi-carrier modulator employing OFDM based on an IDFT and a multi-carrier demodulator employing inverse OFDM based on a DFT is illustrated in Figure 1-6. When the number of sub-carriers increases, the OFDM symbol duration $T_s$ becomes large compared to the duration of the impulse response $\tau_{\text{max}}$ of the channel, and the amount of ISI reduces. However, to completely avoid the effects of ISI and, thus, to maintain the orthogonality between the signals on the sub-carriers, i.e., to also avoid ICI, a guard interval of duration $T_g \geq \tau_{\text{max}}$ has to be inserted between adjacent OFDM symbols. The guard interval is a cyclic extension of each OFDM symbol which is obtained by extending the duration of an OFDM symbol to

$$T'_s = T_g + T_s$$  \hspace{1cm} (3)

The discrete length of the guard interval has to be

$$L_g \geq \left\lceil \frac{\tau_{\text{max}} N_c}{T_s} \right\rceil$$  \hspace{1cm} (4)

samples in order to prevent ISI. The sampled sequence with cyclic extended guard intervals results in

$$x_v = \frac{1}{N_c} \sum_{n=0}^{N_c-1} S_n e^{j2\pi n/v}, v = -L_g, \ldots, N_c - 1.$$  \hspace{1cm} (5)

Advantages:

--- High spectral efficiency due to nearly rectangular frequency spectrum for high number of sub-carriers.
--- Simple digital realization by using the FFT operation.
--- Low complex receivers due to the avoidance of ISI and ICI with a sufficiently long guard interval.
--- Flexible spectrum adaptation can be realized, e.g., notch filtering.
--- Different modulation schemes can be used on individual sub-carriers which are adapted to the transmission conditions on each sub-carrier, e.g., water filling.

Disadvantages:

--- Multi-carrier signals with high peak-to-average power ratio (PAPR) require high lineearmplifiers. Otherwise, performance degradations occur and the out-of-band power will be enhanced.
--- Loss in spectral efficiency due to the guard interval.
--- More sensitive to Doppler spreads then single-carrier modulated systems.
--- Phase noise caused by the imperfections of the transmitter and receiver oscillators influence the system performance.
— Accurate frequency and time synchronization is required.

Applications and Standards:

The key parameters of various multi-carrier-based communications standards for broadcasting, WLAN and WLL, are summarized in Tables 1 to 3.

Table 1: Broadcasting standards DAB and DVB-T[10]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DAB</th>
<th>DVB-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>1.5 MHz</td>
<td>8MHz</td>
</tr>
<tr>
<td>Number of sub-carrier Nc</td>
<td>192 (256 FFT)</td>
<td>384 (512 FFT)</td>
</tr>
<tr>
<td>Symbol duration Ts</td>
<td>125 micro sec.</td>
<td>250 micro sec.</td>
</tr>
<tr>
<td>Carrier spacing Fs</td>
<td>8k Hz</td>
<td>4k Hz</td>
</tr>
<tr>
<td>Guard time Tg</td>
<td>31 micro sec.</td>
<td>62 micro sec.</td>
</tr>
<tr>
<td>Modulation</td>
<td>D_QPSK</td>
<td>QPSK</td>
</tr>
<tr>
<td>FEC coding</td>
<td>Convolution with code rate 1/3 up to 3/4</td>
<td>Reed solomon+ convolutional with code rate ½ up to 5/6</td>
</tr>
<tr>
<td>Max. data rate</td>
<td>1.7 Mbit/s</td>
<td>31.7 Mbit/s</td>
</tr>
</tbody>
</table>

Table 2: Wireless local area network (WLAN) standards [10]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IEEE 802.11a, HIPERLAN/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of sub-carriers Nc</td>
<td>52 (64 FFT)</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Symbol duration Ts</td>
<td>4 micro sec.</td>
</tr>
<tr>
<td>Carrier spacing Fs</td>
<td>312.5 k Hz</td>
</tr>
<tr>
<td>Guard time Tg</td>
<td>0.8 micro sec.</td>
</tr>
<tr>
<td>Modulation</td>
<td>BPSK, QPSK, 16-QAM, 64-QAM</td>
</tr>
<tr>
<td>FEC coding</td>
<td>Convolution with code rate up to 3/4</td>
</tr>
<tr>
<td>Max. data rate</td>
<td>54 Mbit/s</td>
</tr>
</tbody>
</table>

Table 3: Wireless local loop (WLL) standards[10]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Draft IEEE 802.16a, HIPERMAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>From 1.5 to 28 MHz</td>
</tr>
<tr>
<td>Number of sub-carrier Nc</td>
<td>256 (OFDM mode)</td>
</tr>
<tr>
<td>Symbol duration Ts</td>
<td>From 8 to 125 micro sec. (depending in bandwidth)</td>
</tr>
<tr>
<td>Guard time Tg</td>
<td>From 1/32 up to ¼ of Ts</td>
</tr>
<tr>
<td>modulation</td>
<td>QPSK&lt; 16-QAM and 64-QAM</td>
</tr>
<tr>
<td>FEC coding</td>
<td>Reed solomon+ convolutional with code rate ½ up to 5/6</td>
</tr>
<tr>
<td>Max. data rate</td>
<td>Up to 26 Mbits/s</td>
</tr>
</tbody>
</table>


The effect of spectrum sensing errors on the performance of cognitive radio transmission based on orthogonal frequency division multiplexing is evaluated by deriving analytical expressions for average capacity and the average bit error rate as functions of different spectrum sensing parameters and data transmission parameters in the Rayleigh fading channels.

COGNITIVE radio is a promising solution to the problem of “spectrum scarcity” caused by the rapid development of wireless services [1]. It reuses the licensed frequency bands that are not occupied by the licensed users at some specific times in some specific locations [2]. Most cognitive radios have two important functions: spectrum sensing that detects whether the licensed band is free and data transmission that transmits cognitive radio data if the licensed band is free. In the proposed IEEE 802.22 standard [3], these two functions are performed sequentially in each frame that is divided into two periods. The first period is the “quiet” period where cognitive radio receives signals from the licensed band to conduct spectrum sensing, and the second period is the data transmission period where cognitive radio transmits data to another device. If the licensed band is detected busy in the “quiet” period, cognitive radio will wait for the next frame to perform spectrum sensing again. Once the licensed band is detected free, cognitive radio will transmit its data in the following data transmission period.
1) Since the availability of the licensed frequency bands dynamically changes with time and location, orthogonal frequency division multiplexing (OFDM) is a good candidate for the data transmission of cognitive radio.

2) Interference detection and cancellation for the OFDM-based cognitive radio system were studied.

3) Resource allocation for the OFDM-based cognitive radio system was considered.

Also discuss system model:

Consider an OFDM-based cognitive radio system that operates on \( W \) subcarriers owned by the licensed users, referred to as the primary user hereafter. The cognitive radio user, referred to as the secondary user hereafter, will only access these licensed subcarriers when the primary user is detected absent. The secondary transmission is conducted through consecutive frames. In each frame, the first part is the spectrum sensing period and the second part is the data transmission period. In the spectrum sensing period, all the secondary users stop their transmission and listen to the \( W\) subcarriers to decide whether the primary user is absent. If the primary user is detected in the subcarriers during the sensing period, the secondary users will not transmit any data in the following data transmission period in those subcarriers but will wait until the next frame arrives to conduct spectrum sensing of those subcarriers again.

1) Spectrum sensing
2) OFDM data transmission

**Spectrum sensing:** Assume that the \( N \) detected subcarriers are divided into blocks where the \( q\)-th block contains \( N_q \) subcarriers. Each block corresponds to one channel of the primary user or one primary user. For example, this is the case when a bandwidth of 100 MHz is required for a cognitive radio system operating in the TV white space where each channel only provides 6 to 8 MHz. In this case, the secondary cognitive radio needs to use at least 17 TV channels, each of which corresponds to one block that consists of several subcarriers. This is also the case when a cognitive radio system operates in the licensed frequency bands of the narrowband systems such that the licensed bands from several primary users have to be used in order to achieve high data rate. Let the ordered subcarrier index be from 1 to \( N \). Denote \( \text{vector} (1 \times N_q) \) as the \( 1 \times N_q \) vector that contains the subcarrier indexes in the \( q\)-th block. For example, if the second block contains the eighth, ninth, tenth, and eleventh subcarriers, one has \( N_q = 4 \) and \( \text{vector} (1 \times N_q) = [8 \ 9 \ 10 \ 11] \). Denote \( P_q(H_0) \) as the a priori probability that the \( q\)-th block is vacant, where \( H_0 \) represents the hypothesis that the licensed block is free.

Also, denote \( P_q(H_q) \) as the a priori probability that the \( q\)-th block is occupied, where \( H_q \) represents the hypothesis that the licensed block is busy. As mentioned before, each block corresponds to the same channel of one primary user or one narrowband primary user out of several primary users. Therefore, it is reasonable to assume that the subcarriers in the same block have the same availability. In practice, the values of \( P_q(H_0) \) and \( P_q(H_q) \) depend on how busy the primary traffic in the \( q\)-th block is. If all the blocks have the same primary traffic, one has \( P_q(H_0) = P(H_0) = P_q(H_q) = P(H_q) \) for \( q = 1, 2, \cdots, Q \).

In the first part of the secondary frame, spectrum sensing is performed. The sensing accuracy is completely described by two important measures:

**The probability of detection**

The probability of detection gives the probability that the licensed band is busy and is detected busy.

**The probability of false alarm.**

The probability of false alarm gives the probability that the licensed band is busy while is detected free. In reality, these two measures are often put in one relationship that is determined by the receiver operating characteristics (ROC).

In most spectrum sensing methods the probability of false alarm is fixed to maximize the probability of detection using the Neyman-Pearson rule.

Different sensing methods, different channel conditions and different sample sizes will give different probabilities of detection for the same probability of false alarm. In this paper, since the focus is on the effect of sensing errors on the performance of the OFDM-based cognitive radio transmission, to make the result general, it is assumed that \( P_{dq} = P_q(H_1 \mid H_1) \) denotes the probability of detection and \( P_{f} = P_q(H_1 \mid H_0) \) denotes the probability of false alarm in the spectrum sensing for the \( q\)-th block. In otherwords, any detection methods, channel conditions and samplesizes could be used as long as the probability of detection and the probability of false alarm satisfy these two values.

If the same sensing method with the same sample size is used for all the blocks in the same channel condition, one has \( P_{dq} = P_d \) and \( P_f = P_f \) for \( q = 1, 2, \cdots, Q \).

The situation above may be described by a source emitting two possible outputs at various instants of time. The outputs are referred to as hypotheses. The null hypothesis \( H_0 \) represents a zero (target not present) while the alternative hypothesis \( H_1 \) represents a one (target present), as shown in Figure 7. Each hypothesis corresponds to one or more observations that are represented by random

**Figure 7** Each hypothesis corresponds to one or more observations that are represented by random
variables. Based on the observation values of these random variables, the receiver decides which hypothesis (H₀ or H₁) is true.

Assume that the receiver is to make a decision based on a single observation of the received signal. The range of values that the random variable Y takes constitutes the observation space \( Z \). The observation space is partitioned into two regions \( Z₀ \) and \( Z₁ \), such that if Y lies in \( Z₀ \), the receiver decides in favor of \( H₀ \); while if Y lies in \( Z₁ \), the receiver decides in favor of \( H₁ \), as shown in Figure 2. The observation space \( Z \) is the union of \( Z₀ \) and \( Z₁ \); that is, \( Z = Z₀ U Z₁ \). The probability density functions of Y corresponding to each hypothesis are \( f_{Y|H₀}(y) \) and \( f_{Y|H₁}(y) \), where y is a particular value of the random variable Y. Each time a decision is made, based on some criterion, for this binary hypothesis testing problem, four possible cases can occur:

1. Decide \( H₀ \) when \( H₀ \) is true.
2. Decide \( H₀ \) when \( H₁ \) is true.
3. Decide \( H₁ \) when \( H₀ \) is true.
4. Decide \( H₁ \) when \( H₁ \) is true.

Neyman-Pearson rule:- This the best method of the probability of false alarm is fixed to maximize the probability of detection using the Neyman-Pearson rule. In the previous sections, we have seen that for the Bayes’ criterion we require knowledge of the a priori probabilities and cost assignments for each possible decision. Then we have studied the minimax criterion, which is useful in situations where knowledge of the a priori probabilities is not possible. In many other physical situations, such as radar detection, it is very difficult to assign realistic costs and a priori probabilities. To overcome this difficulty, we use the conditional probabilities of false alarm, \( P_f \), and detection \( P_D \).

The Neyman-Pearson test requires that \( P_f \) be fixed to some value \( \alpha \) while \( P_D \) is maximized. Since \( P_M = 1 - P_D \), maximizing \( P_D \) is equivalent to minimizing \( P_M \). In order to minimize \( P_M \) (maximize \( P_D \)) subject to the constraint that \( P_F = \alpha \), we use the calculus of extrema, and form the objective function \( J \) to be \( J = P_M + P_f \lambda (\lambda - \alpha) \) where \( \lambda (\lambda \geq 0) \) is the Lagrange multiplier. We note that given the observation space \( Z \), there are many decision regions \( Z₁ \) for which \( P_M = \alpha \). The question is to determine those decision regions for which \( P_M \) is minimum. Consequently, we rewrite the objective function \( J \) in terms of the decision region to obtain

\[
J = \int_{Z₀} f_{y|H₁}(y)dy + \lambda \left( \int_{Z₁} f_{y|H₀}(y)dy - \alpha \right)
\]

Can be written as

\[
J = \int_{Z₀} f_{y|H₁}(y)dy + \lambda \left( \int_{Z₁} f_{y|H₀}(y)dy - \alpha \right)
= \lambda (1 - \alpha) + \int_{Z₁} f_{y|H₁}(y)dy - \lambda f_{y|H₀}(y)dy
\]

Hence, \( J \) is minimized when values for which \( f_{y|H₁}(y) > f_{y|H₀}(y) \) are assigned to the decision region \( Z₁ \). The decision rule is, therefore,

\[
\Lambda (y) = \frac{f_{y|H₁}(y)}{f_{y|H₀}(y)} > \frac{H₁}{H₀} \quad \lambda \quad \lambda \text{ (8)}
\]

The threshold \( \eta \) derived from the Bayes’ criterion is equivalent to \( \lambda \), the Lagrange multiplier in the Neyman-Pearson \( (N-P) \) test for which the probability of false alarm is fixed to the value \( \alpha \). If we define the conditional density of \( \Lambda \) given that \( H₀ \) is true as \( f_{\Lambda|H₀}(\Lambda|H₀) \), then \( Pₚ = \alpha \) may be rewritten as:

\[
P_f = \int_{Z₀} f_{y|H₀}(y)dy = \int_{\lambda} f_{\Lambda|H₀}(\Lambda|H₀) \, d\Lambda
\]

The test is called most powerful of level \( \alpha \) if its probability of rejecting \( H₀ \) is \( \alpha \).

OFDM data Transmission: We will analyze the performance of the OFDM based cognitive radio transmission for the ideal case without CFO as well as for the practical case with CFO in terms of both average capacity and average bit error rate (BER).
RESULTS:
1) OFDM Transmitter part output:

2) Data Received scatter plot:

3) Final data received output:

4) RayleighPd versus SNR:
5) Probability of missed detection and probability of false alarm:

![Graph showing probability of missed detection and probability of false alarm]

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