Cognitive Radio for Short Range Systems based on Ultra-Wideband

ABDULLAH AL-MAMUN
MOHAMMAD RAFIQ ULLAH

This thesis is presented as part of Degree of Master of Science in Electrical Engineering

June 2011
Abstract

Cognitive Radio (CR) has been proposed as a promising and effective technology to improve radio spectrum utilization. It can change its transmitter parameters depending on the environment in which it operate based on interaction. In CR, a number of different methods of spectrum sensing are used to identify the presence of signal transmission. Among them, the multitaper method (MTM), has been investigated in this thesis paper at the same time with other sensing methods, recently seems to be the best choice for spectrum sensing CR because of its accurate identification and estimation, quick computation, and regularization.

This thesis paper is examining how CR can be utilized in short range systems based on Ultra-Wideband (UWB). UWB is a promising technology in wireless communication use for high speed data transmission with low power utilization or long distance localization in both military, radar, sensor, data collection, tracking or commercial application. UWB has the ability to move between very low data rate or very high data rate, short range distance or long range distance applications. Impulse radio UWB (IR-UWB) shows some impressive characteristics in short-range communication systems with varieties of throughput option including high data rates. The strong synergy between the aims of CR and features of IR-UWB has been shown in this thesis. Our key objective is to understand how CR can be applied to UWB systems.
Acknowledgement

All praises and thanks to Almighty ALLAH for letting us complete this thesis successfully.

We owe our deepest gratitude and respect to our supervisor, Maria Erman, whose encouragement and friendly guidance help us to successfully complete this thesis. We are also grateful to our examiner Dr. Jörgen Nordberg and appreciate his contributions.

We are thankful to the Faculty and Staff members of Blekinge Institute of Technology (BTH) for giving us the opportunity to pursue our Master degree in such a wonderful environment.

Finally, we would like to extend our thanks to our honourable parents and family for their immeasurable patience and support during our course work. Further thanks should also go to all friends who made our life much easier and enjoyable during our study.
Contents

Chapter 1 ............................................................................................................................................... 1
Introduction ........................................................................................................................................ 1
1.1 Motivation ................................................................................................................................... 1
1.2 Objectives ................................................................................................................................... 2
1.3 Thesis Outline ............................................................................................................................. 2

Chapter 2 ........................................................................................................................................... 3
Cognitive radio .................................................................................................................................. 3
2.1 What is Cognitive Radio? ........................................................................................................... 3
2.2 Spectrum sensing ......................................................................................................................... 3
2.2.1 Spectrum holes ....................................................................................................................... 4
2.2.2 Interference Temperature ....................................................................................................... 5
2.3 Licensed and Unlicensed Spectrum ........................................................................................... 6
2.4 The Hidden Node Problem ....................................................................................................... 7
2.5 IEEE 802.22 ................................................................................................................................ 8

Chapter 3 ......................................................................................................................................... 11
Spectrum Sensing ............................................................................................................................... 11
3.1 Introduction .................................................................................................................................. 11
3.2 Spectrum Sensing Methods ......................................................................................................... 11
3.2.1 Match Filter Detection .......................................................................................................... 11
3.2.2 Energy Detection .................................................................................................................. 12
3.2.3 Multiple Taper Spectrum Estimation .................................................................................... 15
3.2.4 Cyclostationary-Based Sensing ........................................................................................... 18
3.3 Cooperative Spectrum Sensing .................................................................................................. 20

Chapter 4 ......................................................................................................................................... 23
Ultra-Wideband (UWB) ...................................................................................................................... 23
4.1 Introduction .................................................................................................................................. 23
4.2 UWB Technology Fundamentals ............................................................................................... 23
4.2.1 Advantages of UWB ............................................................................................................. 23
4.3 Types of UWB .............................................................................................................................. 24
4.3.1 Multi-band OFDM ................................................................................................................ 25
4.3.2 IR-UWB .................................................................................................................................... 25
List of Figures

Figure 2. 1- Spatial spectrum holes [52] .......................................................... 4
Figure 2. 2- Interference temperature ............................................................... 5
Figure 2. 3- Hidden node problem in cognitive radio ........................................ 7
Figure 2. 4- Incumbent operators in the range of IEEE 802.22 network .............. 9
Figure 2. 5- A hidden incumbent receiver problem .......................................... 10

Figure 3. 1- Block diagram of energy detection in time domain ......................... 12
Figure 3. 2- Block diagram of energy detection in frequency domain ................. 12
Figure 3. 3- Non-coherent detection for different SNR values ......................... 14
Figure 3. 4- Multitaper power spectral density estimation of Slepian sequence for different windows ......................................................... 18
Figure 3. 5- Implementation of a cyclostationary feature detection .................... 18
Figure 3. 6- Modulated signals ....................................................................... 19
Figure 3. 7- Cooperative spectrum sensing .................................................... 21

Figure 4. 1(a)- UWB spectral mask and FCC Part 15 limits [34]. 4.1(b)- Spectrum of conventional radio signal (narrowband) versus UWB signal ........................................... 24
Figure 4. 2- Idealized UWB pulses in Time domain ......................................... 26
Figure 4. 3- Different modulation options for IR-UWB system ......................... 29

Figure 6. 1- The probability of detection for different data samples N. ................. 38
Figure 6. 2(a)- Estimation of the magnitude-squared coherence using the multitaper method. (b)- The coherence multitaper method with the white Gaussian signal ........................................ 39
Figure 6. 3- Comparison of DPSS and Kaiser window transforms .................... 40
Figure 6. 4- Comparison of DPSS, Hamming and Tukey window transforms ....... 41
Figure 6. 5- Error probability of M-ary PAM signal ........................................ 42
Figure 6. 6- Error probability of M-ary PPM signal ....................................... 43
Figure 6. 7- Error probability for M-ary PAM and M-ary PPM signals .............. 43
Figure 6. 8- Performance of different RAKE receivers ..................................... 45
Figure 6. 9- Different pulse shapes and spectra of Raised cosine windows and Root raised cosine windows with different roll-off factors α=0.3, α=0.5 and α=0.9 ........................................ 47
### List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC</td>
<td>Analog-to-digital converter</td>
</tr>
<tr>
<td>BER</td>
<td>Bit-error rate</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary phase shift keying</td>
</tr>
<tr>
<td>BS</td>
<td>Base station</td>
</tr>
<tr>
<td>CR</td>
<td>Cognitive radio</td>
</tr>
<tr>
<td>CPEs</td>
<td>Customer Premise Equipments</td>
</tr>
<tr>
<td>EIRP</td>
<td>Equivalent/Effective isotropically radiated power</td>
</tr>
<tr>
<td>DARPA</td>
<td>Defence Advance Research Projects Agency</td>
</tr>
<tr>
<td>DoS</td>
<td>Denial of Service</td>
</tr>
<tr>
<td>DPSS</td>
<td>Discrete Prolate Spheroidal Sequences</td>
</tr>
<tr>
<td>DSS</td>
<td>Distributed Spectrum Sensing</td>
</tr>
<tr>
<td>DS</td>
<td>Direct sequence</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
</tr>
<tr>
<td>FIFO</td>
<td>First-In-First-Out</td>
</tr>
<tr>
<td>ISI</td>
<td>Intersymbol interference</td>
</tr>
<tr>
<td>IR-UWB</td>
<td>Impulse Radio Ultra Wideband</td>
</tr>
<tr>
<td>LOS</td>
<td>Line-of-Sight</td>
</tr>
<tr>
<td>LPD</td>
<td>Low probability of detection</td>
</tr>
<tr>
<td>MTM</td>
<td>Multitaper Method</td>
</tr>
<tr>
<td>NLOS</td>
<td>Non-Line-of-Sight</td>
</tr>
<tr>
<td>OOK</td>
<td>On-Off Keying</td>
</tr>
<tr>
<td>PARP</td>
<td>Peak to average power ratio</td>
</tr>
<tr>
<td>PSK</td>
<td>Phase-Shift Keying</td>
</tr>
<tr>
<td>PPM</td>
<td>Pulse Position Modulation</td>
</tr>
<tr>
<td>PSM</td>
<td>Pulse Shape Modulation</td>
</tr>
<tr>
<td>PAM</td>
<td>Pulse amplitude modulation</td>
</tr>
<tr>
<td>PU</td>
<td>Primary user</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>SDR</td>
<td>Software-defined radio</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
</tr>
<tr>
<td>SCD</td>
<td>Spectrum correlation density</td>
</tr>
<tr>
<td>UWB</td>
<td>Ultra Wideband</td>
</tr>
<tr>
<td>WRAN</td>
<td>Wireless Regional Area Network</td>
</tr>
<tr>
<td>WPAN</td>
<td>Wireless Personal Area Network</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Motivation

The telecommunications industry is growing rapidly over the past decade and in the meantime, wireless standards are also growing very rapidly that are making a very difficult situation in case of radio spectrum in wireless communication. The electromagnetic radio spectrum which is a precious natural resource, used by transmitters and receivers, is of limited physical extent and licensed by governments [48]. In reality, a large part of the licensed bands of the radio spectrum, those allocated for amateur radio, television broadcasting, and paging, are poorly utilized [49]. According to the Federal Communications Commission (FCC) [49], spectrum utilization varies from 15% to 85%. On the other hand, the Defence Advance Research Projects Agency (DARPA) showed that only 2% of the spectrum is underutilized at any given time [50].

This situation with poorly used spectrum can be stopped by making it possible for secondary user to utilize and access the spectrum hole vacant by the primary user (PU) at the right time and space. Cognitive radio (coined by Joseph Mitola III in 1999) [51], including software-defined radio (SDR), has the ability to solve the spectrum underutilization problem and exploit the spectrum holes without interfering any PUs.

UWB technology is a suitable and potential transmission technique for implementing cognitive radio (CR) networks because it has some instrumental features to fulfil some of the key requirements of CR.

UWB is a promising technology in wireless transmission system with large bandwidth for both military, radar, sensor, data collection, tracking or commercial applications. The tempting features of UWB show impressive characteristics in short-range or medium-range communication system with varieties of throughput options including high-data-rates. UWB can coexist in the same spectral domains with other primary or secondary users. UWB has some unique advantages like: low power spectrum density, short pulse with high data rate communication, hardware simplicity, low cost and low complexity, low fade margins, penetration capability, etc.

UWB based CR is considered as one of the best candidates for the next generation short range wireless communication technology. Recently, the activities of UWB based CR has been widely investigated which may carry a significant role in modern wireless
communication system. UWB systems have some exceptional capabilities that can help UWB to endow extra intelligent features with CR:

- negligible interference
- dynamic spectrum
- sensing and channel detection capability
- multiple accesses
- ensure security and QoS
- doesn’t required any license while spectrum utilization.

1.2 Objectives

The Multitaper spectrum, which is one kind of sensing method, seems to be the most appealing one for spectrum sensing CR because of its accurate identification and estimation and low computational complexity. Multitaper uses small set of tapers and multiple orthogonal prototype filters to reduce the variance. The Fourier transform of a Slepian sequence, originally known as discrete prolate spheroidal sequences (DPSS), gives maximum energy density inside a given bandwidth and less spectral leakage with better specifications has been investigated in this paper and shows that no other window in signal processing can satisfy this property.

The UWB system will also be investigated how it can be applied in CR as well as the relation between the features of impulse radio UWB (IR-UWB) and the aim of cognitive radio. The performance of UWB modulation techniques and UWB RAKE receivers will also be investigated in this paper.

1.3 Thesis Outline

Chapter 2: Covers the introduction of Cognitive radio and some fundamental issues of spectrum sensing.

Chapter 3: Cover details about spectrum sensing methods.

Chapter 4: Covers basic fundamentals, types, and modulation techniques of UWB.

Chapter 5: Covers the combination of UWB and Cognitive radio with the purpose of the improvement of spectrum utilization.

Chapter 6: Covers the simulations and results. All the simulations have been done in Matlab.

Chapter 7: Covers conclusions of the thesis paper.
Chapter 2

Cognitive radio

2.1 What is Cognitive Radio?

"Cognitive radio is a radio of an intelligent wireless communication system that senses and is aware of its surrounding environment, and capable to use or share the spectrum in an opportunistic manner without interfering the licensed users”

A cognitive radio (CR) holds the following characteristics: to perceive the surrounding environment, create experience of intentions and self-awareness, reconfigurability, and learn the capability to select specific actions to reach a performance goal with a non-interference basis. Inherent intelligence is the core of a CR that allows to scan all possible spectrum holes before making an intelligent decision on how and when to make use of a particular sector of the spectrum for communications.

Hence, the key challenges of CR are: handling the non-interference rules with any primary users – for instance, by solving hidden node problem (or exposed node problem), channel identification, provide security, and dynamic spectrum management and transmit power control which is carried out in the transmitter.

2.2 Spectrum sensing

The radio spectrum is a natural resource and referred as “lifeblood” [28]. Spectrum sensing enables secondary users or unlicensed users to exploit the unused part of the radio spectrum in a lower priority basis without causing interference to the licensed or primary users. Spectrum sensing must have to gain the awareness about interference temperature and presence of licensed users. The details of spectrum sensing are discussed in chapter 3.

Some tasks of spectrum sensing are:

1) gain spectrum access awareness
2) identify and detect spectrum holes
3) resolve the spectrum of each spectrum hole
4) working with sensing accuracy in order to determine the performance of CR networks
5) classify the signal
2.2.1 Spectrum holes

Spectrum holes are kinds of sub-bands of the radio spectrum that are underutilized (in part or in full) as a secondary user at a particular geographic region of space-time-frequency [48]. Spectrum holes opportunities occur when PUs are not using the spectrum bands temporarily and CR is designed to exploit these spectrum holes. Spectrum holes can be roughly divided into temporal spectrum holes and spatial spectrum holes [52].

A temporal spectrum hole occurs when a primary transmitter is idle over the spectrum band for a certain period of time. The CR may then opportunistically transmit on the spectrum channel during the idle time without causing any interference. The CR user may need a similar detection sensitivity as regular primary receivers in order to make it easy for CR to detect the primary users activity [52].

Spatial spectrum holes, as shown in Figure 2.1, occurs when the PU uses the spectrum band in a restricted boundary area and the CR, who are outside the area, can utilize this band without causing any harmful interference to PUs [52]. In order to avoid the harmful interference to the PU receiver, the CR transmitter must have a proper detection capability so that it can successfully sense the presence or absence of the PUs at any location.

![Figure 2.1: Spatial spectrum holes](image)

**Figure 2.1: Spatial spectrum holes [52].**
2.2.2 Interference Temperature

Traditionally, interference is transmitter-centric and can be controlled through the radiated power, out-of-band emissions, and location of the individual transmitter. But actually interference operates at the receiver [5]. The concept of interference temperature, proposed by the Federal Communications Commission (FCC) in 2003, has been planned to limit the power and bandwidth of new systems that are available without corrupting the existing systems so that cooperation of different radio users in the same spectrum space can be allowed. An interference temperature model is illustrated in Figure 2.2. The RF noise floor has the possibility to rise due to unpredictable appearance of new sources of interference which causes progressive degradation of the signal coverage [31]. So the recommendation of interference temperature is essential in this case.

More precisely, it can say, interference temperature $T_I$ is:

$$T_I = T_N + I_T \tag{1}$$

where $T_N$ is the constant noise temperature and $I_T$ is the interference term caused by the interference environment.

At the output terminals of the antenna, the received RF power could be calculated as:

$$P = kT_I B \tag{2}$$

where $P$ is the average interference power in Watts, $k$ is Boltzmann’s Constant (1.38 $\times$ $10^{-23}$ Joules/Kelvin), $B$ is bandwidth in Hertz, and $T_I$ is the interference temperature in Kelvin.

![Figure 2.2- Interference temperature.](image-url)
Two possible interference models named ideal model and generalized model are constructed in [46]. In the ideal model, priori knowledge of the RF environment is required to distinguish licensed signals from noise and interference and also attempt to limit the interference to licensed signals to set the goal:

\[ T_i + \frac{M_i P}{k B_i} \leq T_L, \quad \forall 1 \leq i \leq n \]  

where \( M_i \) is a constant and \( 0 \leq M_i \leq 1 \), \( n \) is the licensed signal, \( P \) is the average interference power in Watts, \( B \) is bandwidth in Hertz, and \( T_i \) is the interference temperature in Kelvin, and \( T_L \) is the interference temperature limit. \( M_i \) represents multiplicative attenuation between the licensed receiver and the unlicensed transmitter due to fading and path loss. \( T_L \) defines the maximum amount of tolerable interference for a receiver in any particular location with a given frequency band.

In the generalized model, priori knowledge of the RF environment is not required and the interference temperature can be calculated as:

\[ T_i + \frac{M P}{k B_f} \leq T_L \]  

where \( B_f \) is not just the licensed signals frequency band but is the entire frequency range.

2.3 Licensed and Unlicensed Spectrum

The number of commercial licensed spectrum has nearly doubled over the past decade, while the number of unlicensed spectrum has nearly quadrupled. The licensed spectrum operates over particular frequencies of a wireless transmitter consistent to FCC authorization. The license holder retain the spectrum for public safety especially in telecommunication sectors and some other public purposes i.e., broadcast of FM, AM, and TV. Licensed spectrum offers negligible interference, assure QOS, high reliability, high power levels, ability to penetrate obstacles and security. All these benefits make the licensed spectrum more costly.

CR can use two categories of licensed spectrum: cooperative use, and non-cooperative use [47]. Under cooperative use, CR use the licensed band on its own frequencies or others frequency licensed spectrum with their permission. On the other hand, under non-cooperative use, CR use the others frequency licensed spectrum without their permission.

The unlicensed spectrum, also known as licensed-by-rule and licensed-free spectrum, operates at particular frequencies of a wireless transmitter inconsistent to FCC spectrum authorization. As the unlicensed device does not require a license, a number of unlimited users can share the same unlicensed spectrum which could cause unexpected interference at any time and which is why QOS can not be assured. This unlicensed device always behaves as a secondary user and operates like not-to-interfere basis [28]. An unlicensed operation occurs in many spectrum bands on a much shorter time scale and at extremely low power.
The most commonly used unlicensed frequencies are 900 MHz, 2.4 GHz, 5 GHz, and above 60 GHz. The 5.4 GHz to 5.8 GHz unlicensed frequency band are favourites in Europe.

2.4 The Hidden Node Problem

The hidden node problem is one of the single most important issues in a cognitive radio network. The effect of fading, which is observed by secondary users, can result in this kind of problem. There are mainly two types of fading: multipath fading which is frequency dependent and can change significantly over small changes in location, and shadowing which is frequency independent and have no interaction with signal strength. There is a chance for secondary users to falsely sense the primary user’s transmission due to noise or interference in the wireless environment. An illustration of the hidden node problem is shown in Figure 2.3. Here, a secondary user cannot detect the primary users signal due to shadowing or multipath fading and causes unwanted interference to the primary receiver because primary transmitter signal could not be detected.

In [7], distributed spectrum sensing (DSS) is proposed as a solution for the hidden node problem that can be assuage by requiring multiple secondary users cooperating with each other in spectrum sensing. Similarly in [32], in order to overcome the hidden node problem, the detection sensitivity of cognitive radio should be better than the primary radio system by a large margin (for example, 20-30 dB). A two-way handshake method proposed by Karn [33] can also be a good candidate to alleviate the hidden node problem.

![Figure 2.3- Hidden node problem in cognitive radio.](image-url)
2.5 IEEE 802.22

The IEEE 802.22 is the first wireless access cognitive radio standard. The IEEE 802.22 working group defines a system for a cognitive Wireless Regional Area Network (WRAN) using unused or white spaces within rural areas or in the TV frequency spectrum between 54 and 862MHz. The development of the IEEE 802.22 WRAN standard is aimed at sharing of white space or unused spectrum allocated to the TV Broadcast Service on a non-interfering basis in spectrum with the help of cognitive radio techniques to allow to bring broadband access to less populated density areas, typical of rural environments where there is a large number of vacant TV channels or insufficient level of broadband access service, and remote areas. The IEEE 802.22 WRAN are designed so that no harmful interference is caused while operating the TV broadcast and that’s why WRAN will be a cheaper solution for a broadband network. The IEEE 802.22 is responsible for protecting licensed wireless microphone operation and for this they must respond quickly without interfering to the licensed transmissions while spectrum availability changes.

The 802.22 WRAN consists of a Base station (BS) and a number of client stations, referred to as Customer Premise Equipments (CPEs). The tasks of both BS and CPEs are spectrum sensing, transmitting/receiving data and assure the Quality of Service (QoS). BS and CPEs can trace the licensed incumbents and their used channels by sensing the channel periodically. If the licensed incumbents occupy any channels which are under the IEEE 802.22 network, the IEEE 802.22 should vacant the channel as a priority basis within channel move time (2 second) and search for an other unused vacant channel and switch to it. In IEEE 802.22 WRAN, BS manages the on-air activity within the cell so that it can manage its own cell and this cell has unique IEEE 802 MAC address [25].

Incumbent sensing measurement and detection are unique and essential for the 802.22 standard. Some of 802.22 standards are dependent on it. At any point of time, a multitude of incumbents (e.g. TV, DTV and FCC Part 74 devices such as wireless microphones) may operate in the same area as IEEE 802.22 WRAN network which is shown in Figure 2.4. The primary task of all IEEE 802.22 equipments is to sense the presence of incumbent. BS and CPEs both participate in incumbent detection to co-exist with the incumbents and allows the sensing task to be distributed and make better room for BS to indentify the localized incumbents so that only cognitive user would be able to sense under the 802.22 BS [27, 28]. To allocate the VHF or UHF with the incumbents, an incumbent avoidance techniques (a multititiered approach to sensing that aims to have a minimal impact on overall system performance) needs to be build [28].
Some drawbacks among IEEE 802.22 are self-coexistence and the hidden incumbent problem. The hidden incumbent problem, shown in Figure 2.5, occurs when the CPE is in the overlap region between the BS and an incumbent coverage. The two reasons behind this are [29]:

1) Both the BS and the CPEs perform sensing periodically to discover the presence of incumbent transmission. However if the CPE notice an incumbent transmission in-band, interference could occur by loosing synchronization with the BS because at that time the CPE might have problem reporting to the BS since it is interfered by incumbent transmission.

2) If the CPE has just switched on, the first task will be to scan for 802.22 BS channels. If the CPE is in the overlap region it will not sense the 802.22 service because it will not have the ability to decode the BS broadcast.

Besides this, there are also some security threats that exploit the vulnerabilities of 802.22’s security protocols: Denial of Service (DoS), Replay Attacks, Incumbent Signal Emulation, and Security Vulnerabilities in Coexistence Mechanisms, etc [26].
Figure 2. 5- A hidden incumbent receiver problem.

In [30], the IEEE 802.22 functional requirements are:

- Fixed point-to-multi-point access only.
- BS controls all transmit parameters and characteristics in the network.
- BS is professionally installed and maintained.
- Location awareness for all devices in the network
- 1 W transmitter power with a maximum of 4 W EIRP.
- BS uses an up-to-date database augmented by distributed sensing to determine channel availability.
- The CPE antenna is to be installed outdoors at least 10 m above ground.
- The CPE cannot transmit unless it has successfully associated with a BS.
Chapter 3

Spectrum Sensing

3.1 Introduction

The demand of transferring with a higher data rate is increasing but current static frequency allocation cannot fulfil this requirement because of frequency spectrum limitation. Cognitive radio can be an attractive solution for this kind of problem by utilizing unused frequency bands [1]. In the case of intelligent wireless communication systems, cognitive radio is able to sense and be aware of its surroundings which make spectrum sensing an ideal requirement to realize. In wireless communications, radio spectrum is referred to as ‘lifeblood’. The unlicensed user, with the help of spectrum sensing can sense the environment to detect unused spectrum without interfering the primary network.

3.2 Spectrum Sensing Methods

Spectrum sensing can be divided into two methods: 1) parametric methods based on match filter detection, energy detection, and cyclostationary-based sensing ii) nonparametric spectrum estimator based on multitaper method.

3.2.1 Match Filter Detection

A match filter is the optimal detection of primary users when the information of a transmitted signal is known and can maximize the received signal-to-noise ratio (SNR) [3]. An important drawback of matched filter detection is that each primary user of cognitive radio would need a dedicated receiver. So cognitive radio needs a perfect knowledge of the primary users signal modulation type and order bandwidth, operation frequency, pulse shaping, packet format, etc. Another drawback of the match filter is that different receiver algorithms require performing for detection in case of larger power consumption. However on the other hand, the main advantage of the match filter is that it can achieve a high processing gain (probability of false alarm or probability of miss detection) in short time since only O(1/SNR) samples are required.
3.2.2 Energy Detection

When the secondary receiver is unable to locate the primary user (PU) signal with unknown signal strength and location, energy detection assists as the optimal detector if the detector is recognizable with receiver signal power of random Gaussian noise. Energy detection is also known as radiometry or periodogram and is the classical method for identifying an unknown signal that quantify the received signal energy over an observation time window [5]. Figure-3.1 and 3.2 shows the block diagram of energy detection. It can perform both in time and frequency domain. At first, in the case of time domain, a bandpass filter is passed through a target signal in order to measure the strength of a signal in time domain [6]. Assumed that the input signal $y(t)$ is real. This signal is transformed into digital form using an analogue-to-digital converter (ADC). After that, the received signal is squared and averaged, and then the output is compared with a threshold, $\lambda$, to decide if the primary user exists or not. That means that the decision is made by two binary hypotheses:

$$
y(n) = \begin{cases} 
w(n), & H_0 (\text{signal absent}) \\
x(n) + w(n), & H_1 (\text{signal present}) \end{cases}
$$

(5)

$n = 1, - - - - - , N$, where $N$ is the length of available known pattern.

where, $x(n)$ is the primary users signal to be detected, $w(n)$ is the Additive White Gaussian Noise (AWGN) with zero mean and variance $\sigma^2_w$, i.e. $w(n) = \mathcal{N}(0, \sigma^2_w)$, whereas the received signal is assumed to be zero mean with a variance $\sigma^2_x$, i.e. $x(n) = \mathcal{N}(0, \sigma^2_x)$. The signal to noise ratio (SNR) can be defined as:
The decision statistics $D$ for energy detection can be written as:

$$D = \sum_{n=0}^{N} (y[n])^2 \geq_{H_0}^{H_1} \lambda$$

(7)

The decision statistics is distributed with $2N$ degrees of freedom $\chi^2[7]$. The probability of false alarm ($P_F$) and probability of detection ($P_D$) can be calculated as:

$$P_F = P_r (D > \lambda \mid H_0) = 1 - \Gamma (N, \frac{\lambda}{\sigma_w^2})$$

(8)

$$P_D = P_r (D > \lambda \mid H_1) = 1 - \Gamma (N, \frac{\lambda}{\sigma_n^2 + \sigma_w^2})$$

(9)

$$\Gamma(N, a) = \frac{1}{\Gamma(a)} \int_0^{N} e^{-t} t^{a-1} dt$$

Where $\Gamma(x, y)$ and $\Gamma(x)$ are incomplete and complete gamma functions respectively.

The probability of false alarm ($P_F$) is the probability of declaring a channel occupied when it is vacant, i.e. the decision that is based on some statistics transcends the threshold when only noise is present. Normally, the probability of false alarm is limited so that it does not transcend the desired value; otherwise performance will be poor [8]. The probability of detection ($P_D$), is the probability of declaring the channel occupied when it is really occupied. The requirement for both probability of false alarm and probability of detection in IEEE 802.22 is defined in [9], which are $P_F \leq 0.1$ and $P_D \geq 0.9$.

Figure 3.3 shows that at different SNR, the threshold detection capability differs. This figure clearly shows that the performance of the detection improves by increasing the SNR values. Here, the average code length is set to 15, i.e. $N=15$.

Energy detection relies on accurate noise power. Noise power could be different from real noise power due to noise uncertainty [12]. Actual noise power can be calculated as

$$\sigma^2_a \in \left[ \frac{1}{a} \sigma_n^2, a \sigma_n^2 \right]$$
Figure 3. 3- Non-coherent detection for different SNR values.

Let, estimated noise power is $\hat{\sigma}_n^2 = \alpha \sigma_n^2$. So the noise uncertainty factor (in dB) is

$$B = \max \{10 \log_{10} \alpha\}$$  \hspace{1cm} (10)

Let, $\alpha$ (in dB) be between [-B, B] [11, 12]. In practically the noise uncertainty of receiving device is at least about 1-2 dB.

Energy detection has some major problems with regards to noise uncertainty that causes difficulties to obtain accurate noise power like: 1) non-linearity of components; 2) thermal noise in components; 3) noise due to transmissions by others [10]. In these cases, reduced rank eigenvalue can be used to overcome the shortages [1, 13]. This kinds method is effective for various kinds of signal detection and does not require any kind of knowledge of the signal, the channel and noise power and can be able to reduce the computational load and make it easier for the spectrum in case of simple time-domain windowing [10].

The Fourier transform of the input signal is:

$$x_k(t) \xrightarrow{\text{Fourier Trans}} X_k(\omega)$$  \hspace{1cm} (11)

where, $x_k(t)$ is a real signal where $t$ indicates a fast time parameter. $X_k(\omega)$ is the Fourier transform of a real signal and $k$ indicates kth sampled time frame increasing with a slow time
scale [13]. The reduced rank algorithm uses an auto-correlation estimate at small lag($\tau$) defined by $\omega_m$, $m \in [1, M]$, and is given by [13]

$$R_{xx}(\tau) = \frac{2}{M} \sum_{m=1}^{M} |X(\omega_m)|^2 e^{2j\pi \omega_m \tau}$$  \hspace{1cm} (12)

lag($\tau$) can be expressed as: $\tau = ndt = \frac{n}{F_s}$, where $F_s$ is the sampling frequency. The correlation matrix linked with rank $N$ is given by

$$R = \begin{bmatrix} R_{xx}(0) & R_{xx}(1) & \cdots & R_{xx}(N-1) \\ \vdots & \ddots & \vdots \\ R_{xx}(N-1) & \cdots & R_{xx}(2)R_{xx}(1)R_{xx}(0) \end{bmatrix}$$  \hspace{1cm} (13)

This matrix $R$ is self-adjoint or a Hermitian matrix. Let $\lambda_i$ be the eigenvalue of the correlation matrix $R$. The noise floor $\eta$ in dBm/Hz which is given by lowest value is then [13]:

$$\eta_{dB} = 10\log_{10}(\min(\lambda_i))$$  \hspace{1cm} (14)

And also the bounded adaptive threshold is [13]:

$$KT \times NF \leq \eta \leq \eta_{\text{upper bound}}$$

where $KT$ is the thermal noise with Boltzmann’s constant $K$ ($1.38054 \times 10^{-23}$ joules/Kelvin) and temperature $T$ in degrees Kelvin (i.e., 295K). NF is the lowest noise figure and $\eta_{\text{upper bound}}$ is the upper bound to estimate the adaptive noise floor.

In conclusion, advantages of energy detection are:

1) Short sensing time which is why it is more generic
2) Simple to implement
3) Low computational and implementation complexities.

Similarly, there are also some disadvantages which are:

1) Detection of spread spectrum signal
2) Threshold setting
3) Performance effects due to background interference and noise uncertainty.

3.2.3. Multitaper Spectrum Estimation

The multitaper spectrum estimation method which was introduced by Thomson [14] can be used to solve the bias-variance dilemma that causes some problems like: i) windowing (tapering) that reduced the bias of power-spectrum estimation of a time series, and ii) the cost, which is obtained by the improvement of estimated variance, reduced the effective
sample size [31]. Thomson suggested using a bank of optimal band pass filters in replacement of a rectangular window. To improve the bias-variance, it uses multiple set of K orthogonal prototype filters. The multitaper method shows the components of a spectrum containing both continuous and singular components. It is widely used to study the geophysical signal analysis like: atmospheric, oceanic data, geochemical tracer data, paleoclimatic data and seismological data, analysing terrestrial free oscillations; and also used to analyse the relationship between carbon dioxide and global temperature, and oxygen isotoperations. It is also applied to the TV bands using signal measurements. Multitaper uses a small set of taps and multiple orthogonal prototype filters to reduce the variance. The taps are fabricated in such a way that each taper samples the time series in a different fashion. The second taper partially support the first taper when statistical information disposed by the first taper, and in the same way third taper partially recovered the first two tapers, and so on. As the higher-order taper causes unacceptable spectral leakage, some few low-order tapers are employed.

The multitaper Method (MTM) seems to be the best choice for a spectrum sensing CR because of its accurate identification and estimation, quick computation, regularization, and signal classification.

Multitaper spectrums are organized as a weighted sum of the eigenspectra. Multitaper spectral estimation linearly extends the time series in a fixed bandwidth \( f_- \omega \) to \( f_+ \omega \) (here \( \omega = \Delta f/2 \) where \( \Delta f \) is a frequency resolution) in a family of sequence which come from filter coefficients known as a Slepian sequence. The Slepian sequence is used as a solution of the standard eigenvalue problem. Figure 3.4, which shows the multitaper power spectral density estimation of a Slepian sequence for different windows, clearly demonstrates that reducing the windows value will give better frequency resolution with higher variance and less spectral leakage.

The Slepian sequence form a set of orthogonal vectors that helps to expand the time series over frequency band \((f_- \omega \) to \( f_+ \omega \)) [15]. For a given time series \( \{x_k\}_{k=1}^N \), the related complex “eigencoefficients”, \( Y_k(f) \), is defined by the Fourier transform if the product of data with \( \{\omega_k\}_{k=0}^{K-1} \) is [15, 31]:

\[
Y_k(f) = \sum_{t=1}^N \omega_t^k x(t)e^{-j2\pi ft}, \quad k = 0, 1, \ldots, K-1
\]

The Fourier transform of a Slepian sequence gives the maximum energy density. The energy distributions of the eigenspectra are focused inside a resolution bandwidth \( 2W \) and the time-bandwidth product

\[
P = 2NW
\]

determines the degree of freedom that is used to control the variance. Parameters K and P defines a trade off between spectral resolution and variance. An adaptive spectrum estimate based on the first few eigenspectras is [31, 15]

\[
\hat{S}(f) = \frac{\sum_{k=0}^{K-1} \lambda_k(f) |\hat{Y}_k(f)|^2}{\sum_{k=0}^{K-1} \lambda_k(f)}
\]
here, $\lambda_k$ is the eigenvalue related to the Kth eigenspectrum. The spectral estimate $\hat{S}(f)$ is unbiased for denominator in (17) and if choose K=2NW-1, it makes the eigenvalue $\lambda_k$ close to unity [31].

$$K \approx \sum_{k=0}^{K-1} \lambda_k$$

If the samples are taken at uniform time spacing in the case of conventional energy detection, the power spectrum density is [16]:

$$\hat{S}(f) = \frac{1}{N} \left| \sum_{t=1}^{N} x(t)e^{-j2\pi ft} \right|^2$$

Assume that the CR and the PU node both exist in a practical RF environment and also assume that there are M nodes of CR focused on unused spectrum of the primary RF environment with the MTM, then the different eigenspectrums produced by each CR node formulate the spatio-temporal complex matrix M(f) as [16]:

$$M(f) = \begin{bmatrix}
  a_1Y_1^{(1)}(f) & a_1Y_2^{(1)}(f) & \ldots & a_1Y_K^{(1)}(f) \\
  a_2Y_1^{(2)}(f) & a_2Y_2^{(2)}(f) & \ldots & a_2Y_K^{(2)}(f) \\
  \vdots & \vdots & \ddots & \vdots \\
  a_MY_1^{(M)}(f) & a_MY_2^{(M)}(f) & \ldots & a_MY_K^{(M)}(f)
\end{bmatrix}$$

The matrix M(f) has an order of MxK where each row is created by different CR node and each column estimates the eigenspectrum using different tapers.

The performance of MTM with singular value decomposition in [16] takes into two consideration parameters: the number of sensors and the number of tapers which show that decision statistics improve with the increase of the number of sensors simultaneously but the tapers used in the system could cause the unwanted bias problem due to the spectrum estimates. The filter-bank theory described in [31] shows the although the MT is a more powerful spectrum technique than the filter bank spectrum estimator, its practical application in CR could be limited due to its high computational cost. The filter bank spectrum analysis may well take its place. Also [20] shows that although MT has a higher computational complexity compared with the FFT method in TV bands, its noise reduction property can play an important role to correctly identify the free channels in TV bands compared to the FFT method.
Figure 3.4 - Multitaper power spectral density estimation of Slepian sequence for different windows.

3.2.4 Cyclostationary-Based Sensing

The wireless communication device uses the cyclostationary detection method to detect the existence of primary users in the feature detection approach. A block diagram of cyclostationary feature detection is shown in Figure 3.5 [4]. The feature detection can be implemented by applying the FFT cross products for all offsets with windowed averaging.

Figure 3.5 - Implementation of a cyclostationary feature detection.

Cyclostationary can be describe by some modulated signals, which is shown in Figure 3.6. The modulated signals carries hoping sequence, sine wave carriers, cyclic prefix or repeating
Cognitive Radio for Short Range Systems based on Ultra-Wideband

spreading and have the ability to extract those distinct modulated signals features. Two-dimensional spectral correlation is the way to detect these modulated features. Although, these modulated signals are cyclostationary processes which has periodic autocorrelation function and is periodic in time $t$ [17].

$$R_{X}(t + \tau) = R_{X}(t + T_0, \tau)$$

(21)

![Figure 3.6- Modulated signals.](image)

The Fourier transform of the autocorrelation function:

$$R_{X}^{\alpha}(\tau) = \lim_{T \to \infty} \frac{1}{\tau} \int_{T}^{T} x(t + \frac{T}{2})x(t - \frac{T}{2})e^{-j2\pi \alpha t} dt$$

(22)

Where $\alpha$ is the fundamental frequency and $R_{X}^{\alpha}(\tau)$ is called the cyclic autocorrelation function (CAF). The spectrum correlation density (SCD) function is obtained by CAF and can separate the Wide-Sense Stationary noise from primary users signal. Hence this spectral correlation function can be defined as [17, 4].

$$S_{X}^{\alpha}(f) = \lim_{\Delta t \to \infty} \lim_{\tau \to \infty} \frac{1}{\Delta t} \frac{1}{\Delta t} \int_{\Delta t \Delta t}^{\Delta t} X_{T}(t, f + \frac{\alpha}{2})X_{T}^{*}(t, f - \frac{\alpha}{2}) dt$$

(23)

where the spectral component of the cyclostationary signal $X(t)$ with bandwidth $\frac{1}{\tau}$ at frequency $f$ is given by:

$$X_{T}(t, f) = \int_{t-T/2}^{t+T/2} x(u)e^{-j2\pi fu} du$$

(24)
The spectral correlation function of (5) for two binary hypotheses is:

\[ S_{X}^\alpha(f) = \begin{cases} S_{0}^\alpha(f), & \text{Ho (signal absent)} \\ S_{0}^\alpha(f) + S_{1}^\alpha(f), & \text{H1 (signal present)} \end{cases} \] (25)

But as the noise is not a Cyclostationary process, so

\[ S_{0}^\alpha(f) = 0 \quad \forall \alpha \neq 0 \]

The Spectral correlation function for a fixed number of N samples is:

\[ S_{X}^\alpha(f) = \frac{1}{N} \sum_{n=0}^{N} Y_{T}(n, f + \frac{\alpha}{2}) Y_{T}^*(n, f - \frac{\alpha}{2}) \] (26)

where,

\[ Y_{T}(n, f) = \int_{-T/2}^{T/2} y(u)e^{-j2\pi fu} du \] (27)

One of the main advantages of cyclostationary feature detection is its robustness to noise uncertainty. It also has discriminatory capabilities. On the other hand, it has some limitations like: spectral leakage of high amplitude signals, non-linearities, is computationally complex and needs a significantly longer observation time.

### 3.3 Cooperative Spectrum Sensing

Nowadays, fading, shadowing, noise uncertainty, and building penetration losses are the most aspirational issues in spectrum sensing. To alleviate this problem, cooperative spectrum sensing is introduced as a solution in many literature. The motivation behind cooperative sensing in [18] shows that the multipath among the above degraded signals varies with the displacement of antenna that forced the multiple radio, which can reduce the output of low multipath at a single radio, act as a proxy. So, the fading due to multiple realizations is extremely low and cooperation helps to achieve the robustness for spectrum sensing cognitive radio in fading environments and maximize the detection probability or minimize the misdetection probability and the probability of false alarm considerably. Cooperation can reduce the average time to sense the primary users and can solve the hidden node problem.

The performance of cooperative sensing depends on the fading effect, so if the probability of fading is low, then the performance of cooperative sensing will improve. At the same time interference to the primary user is also decreased. On the other hand, independence and trust
issues like malicious and malfunctioning nodes can be a strong obstacle for performance improvement [19].

The performance of cooperative spectrum sensing is shown in Figure 3.7. The secondary users $i$ are grouped to sense the presence of primary users and it measure the local spectrum independently.

After spectrum detection, all the secondary users in a group makes a binary decision $D_i \in \{0, 1\}$, for all $i = 1, \ldots, k$; before forwarding this binary decision to a common receiver. After that the common receiver combines all the binary decisions to make a final decision $H_0$ or $H_1$ to find out the absence or presence of PU [21, 22].

![Figure 3.7 - Cooperative spectrum sensing.](image)

All these binary 1 decisions are combined together at the common receiver dealing with the following role [22]:

$$L = \sum_{i=1}^{K} D_i \mathbb{I}_{H_1} \leq H_0 \eta$$

(28)

The expression (28) shows that at the receiver, the base station decides the PU signal being transmitted when at least $\eta$ out of $K$ cognitive radios are present, i.e., $H_1$. Otherwise the base station decides $H_0$ is present, i.e., PU signals not being transmitted.

In [23], a centralized network based on OFDM is proposed where the access point consisting of a cognitive radio based station and cognitive radio mobile user collects sensing results from all user. The access point sense the channel to performs the channel allocation so that it can adjoin all the requested data rates of each user. An increment update is needed to reduce bandwidth requirements over the control channel if channel coherency time is small. In [24], the base station can exploit the cooperative gain dealing with some issues. First, the expected interference ratio is less than the original sensing parameter when cooperative scheme
increase the detection probability. Second, the time-varying characteristics of the cooperation gain depend on the number of users involved in the cooperation. A distributed cooperative scheme proposed in [4] may be easier to carry out where neighbours are chosen randomly but at the same time, the capacity of the centralized scheme may not achieve. Aggregating several users results with different sensitivities and sensing time can creates a problem in cooperation.
Chapter 4

Ultra-Wideband (UWB)

4.1 Introduction

Ultra-Wideband (UWB) is a promising technology in wireless communication use for high speed data transmission with low power utilization or long distance localization in both military, radar, sensor, data collection, tracking or commercial application. UWB has the ability to move between very low data rate or very high data rate, short range distance or long range distance applications.

4.2 UWB Technology Fundamentals

UWB in wireless system can be describe as a wireless transmission scheme that has a bandwidth of at least 1.5 GHz or a fractional bandwidth of at least 0.25. But the Spectrum Policy Task Force (SPTF) of the Federal Communications Commission (FCC), in 2002, has decided to change the traditional system after received some extensive commentary from many individuals and corporations. The FCC imposes new limitations for UWB transmission instead of the old where a fractional bandwidth is greater than 20% of the centre frequency as shown in Figure 4.1(b) or a bandwidth is greater than 500 MHz. This new regulations is applicable for the unlicensed radio spectrum between the range of 3.1-10.6 GHz at a transmit power of -41 dB/MHz as shown in Figure 4.1(a) under the conditions of both line-of-sight (LOS) and non-line-of-sight (NLOS). Fractional bandwidth is calculated as

\[
\text{fractional bandwidth} = \frac{B}{f_c} = 2 \frac{f_u - f_L}{f_u + f_L}
\]  

(29)

where bandwidth, \( B \triangleq f_u - f_L \) and centre frequency, \( f_c \triangleq (f_u + f_L)/2 \) with upper edge frequency \( f_u \) and lower edge frequency \( f_L \) at -10 dB below the peak emission point.

4.2.1 Advantages of UWB

In wireless communication, UWB has some significant contributions. It offers the following potential advantages over traditional communication systems.
1. In the case of wide radio frequency bandwidth, UWB offers high rate communications, flexible time resolution for tracking and location application, potential gain, and low penetration loss.
2. For short pulse system, UWB offers robust performance under multipath environments.
3. Low power spectra density allows UWB to coexist with other existing users.
4. Provide small hardware simplicity.
5. Provide accurate (<1cm) range information.
6. Low power consumption, low cost and low complexity.
7. Low probability of detection (LPD). Because the high bandwidth of UWB create low spectral densities that makes very difficult to intercepted and decoded by unauthorized receivers.
8. Provide secure communications.

![Figure 4.1(a)- UWB spectral mask and FCC Part 15 limits [34]. 4.1(b)- Spectrum of a conventional radio signal (narrowband) versus UWB signal.](image)

4.3 Types of UWB

The most commonly used UWB technologies are the Impulse Radio based UWB (IR-UWB) and multi-band Orthogonal Frequency Division Multiplexing based UWB (UWB-OFDM). In this paper, only IR-UWB systems are considered because of its simplicity, low cost, simple architecture, excellent multi-path resolving capability, and various modulation techniques.
4.3.1 Multi-band OFDM

Multi-band OFDM, which has spectrum shaping and underlay sensing capabilities, is one of the competitive candidate for CR based UWB in order to detect the presence or absence of PU. Multi-band OFDM divide the spectrum into sub-bands in order to achieve multipath energy efficiently and to reduce the complexity of receiver that are modulated with orthogonal subcarriers [1]. These orthogonal subcarriers also ensure that no interference will take place between them and as a result internal interference is negligible. So considering the sub-band, multi-band OFDM divided the spectrum between 3.1 GHz and 10.6 GHz into 528 MHz sub-bands and use multiband in conjunction. Multi-band OFDM symbols are provided over different sub-bands across both in time and frequency instead of providing over one frequency band.

Large peak to average power ratio (PARP), frequency error, synchronization issues, etc. are the major problems in multi-band OFDM system [36]. To take part as a strong candidate in CR, multi-band OFDM should overcome these.

4.3.2 IR-UWB

Impulse Radio UWB (IR-UWB), a typical UWB signaling method, is carried out by transmitting very short duration, low-power pulses with low duty cycle that are in the order of sub-nanoseconds [1, 37]. This low duty cycle helps to ignore collisions with other in-band wireless communication system. Impulse system is similar with the nerve system or spikes that have small pulses in time and narrowness pulse has a fine time resolution.

IR-UWB is baseband in nature, i.e. carrier-less and there is no intermediate up-conversion and down-conversion frequency needed. The ability of highly resolved multipath helps IR feasible for high-quality, fully mobile short-range indoor radio systems [38]. Also the resolution of multipath below to a nanosecond in differential path delay helps to overcome multipath fading by reducing fading margins in link budgets and may allow to operate in low power transmission [37]. Multipath resolving capability gives IR-UWB an extra features as a precise radar technology as well as a highly accurate ranging and positioning system. IR-UWB provides low cost transmitters and receivers because of simplest implementation techniques. The pulse shape and various modulations are discussed below.

4.3.2.1 UWB Pulse Shape

A typical received UWB pulse shape including Gaussian pulse, Gaussian monocyle (1st derivation of Gaussian pulse) and Gaussian doubler (2nd derivation of Gaussian pulse) are
shown in Figure 4.2 and are easy to generate and they can radiate in an efficient way because they have no DC (direct current) value. It is noted that if Gaussian pulses passes through any linear system they remain Gaussian distributed. Pulse generation, pulse shaping filter and antenna responses affect the received pulse shape. The general formulas for Gaussian monocycle and doublet are modelled by equation in (30) and (31) respectively.

$$G_m = -\frac{t-t_0}{\tau} e^{-\left(\frac{t-t_0}{\tau}\right)^2}$$  \hspace{1cm} (30)

$$G_d = \left[1 - 4\pi \left(\frac{t-t_0}{\tau}\right)^2\right] e^{-2\pi \left(\frac{t-t_0}{\tau}\right)^2}$$  \hspace{1cm} (31)

where $t_0$ is a time offset and $\tau$ is a time constant.

![Ideal UWB pulses in Time domain.](image)

**Figure 4.2 - Ideal UWB pulses in Time domain.**

### 4.3.2.2 Modulation Techniques

Two variants of IR modulation techniques, in order to achieve better and higher communication rates, are Direct Sequence UWB (DS-UWB) and Time Hopping UWB (TH-UWB).
4.3.2.2.1 DS-UWB

Direct sequence (DS) is a powerful and well known multiple access technology by coherently sending power Gaussian shaped pulses at the receiver. Each of DS-UWB has a very short and high-duty-cycle pulse that follows pseudo-random code sequences and transmitted the multiple pulses/bit using bipolar modulation for each pulse [39]. DS-UWB contains some attractive properties like: low peak-to-average power ratio, better use of time-bandwidth resources and robustness to multiuser interference [39].

There are some modulations in DS-UWB that can help to enable data to be carried. Binary phase shift keying (BPSK) is one of the modulation techniques among them. The transmitted signal of DS-UWB for the kth user is [36]:

\[ P_k(t) = \sum_{j=-\infty}^{\infty} p_{k,j} N_{Tc}(t - jT_c) \]  
\[ B_k(t) = \sum_{i=-\infty}^{\infty} B_{k,i} N_T(t - iT) \]

where \( P_{k,j} \) is a periodic sequence of \( k \)th user, also called signature sequence and \( p_{k,j} \in \{+1,-1\} \) and \( N_{Tc}(t) \) is a narrow time limited pulse with \( T_c \) duration. Similarly, \( B_{k,i} \) is the binary data where \( B_{k,i} \in \{-1,+1\} \) and \( N_T(t) \) is similar like \( N_{Tc}(t) \) but \( T \gg T_c \). \( T/T_c = G \), is called processing gain. Multiplying both equations can obtain DS-UWB as [36]:

\[ s_k(t) = P_k(t). B(t) \]  

Assume \( N_u \) users are asynchronously transmitting through AWGN channel and are active in the multiple access system, the received signal at the receiver antenna is [39]:

\[ r(t) = \sum_{k=1}^{N_u} G_k s_k(t - \tau_k) + n(t) \]

where \( s_k(t) \) is BPSK-UWB signal, \( n(t) \) is additive noise at the correlator input modeled as \( N(0,\sigma_n^2) \). \( \{G_k\}_{k=1}^{N_u} \) indicates channel gain for all transmitted signals, and \( \tau_k \) represents time shifts.

For an active single user system in BPSK modulation, the receiver output \( SNR \) is [40]:

\[ SNR_{out} = \frac{N_c G_t^2 E_w}{\sigma^2_n} \]  

where \( E_w \) is the energy of pulse at the transmitter input and \( N_c \) is the number of chips per bit.

The bit-error rate (BER) in BPSK is [40]:

\[ P_e = \frac{1}{2} \text{erfc} \left( \sqrt{SNR_{out}} \right) \]  

Similarly, BER for an active multi-user system is [40]:

\[ P_e = \frac{1}{2} \text{erfc} \left( \sqrt{\left( \frac{2E_b}{N_0} \right)^{-1} + \left( \frac{N_c T_s}{\sigma^2_M (N_u - 1)} \right)^{-1}} \right) \]  

where \( \sigma^2_M = \int_{-T}^{T} R_0^2(\tau) \, d\tau \)

here, \( T \) is the pulse duration and \( R_0(\tau) \) is the autocorrelation of \( N_T \).
4.3.2.2.2 TH-UWB

TH-UWB utilizes low-duty-cycle pulses. In the TH-UWB, the TH sequence acts as a unique code that is applied to each user to specify which segment is used for transmission in each frame interval. Some common modulations of TH-UWB are On-Off Keying (OOK), Pulse Position Modulation (PPM), Phase-Shift Keying (PSK), Pulse Shape Modulation (PSM), and pulse amplitude modulation (PAM). Some of these modulations are illustrated in Figure 4.3.

The PAM modulation, based on encoding the data in the amplitude of the impulses, can be expressed as:
where $A_k$ is the phase amplitude of $k$th user and $T_f$ is the duration of a frame.

OOK modulation, the simplest pulse modulation that represents a digital data bit by 0 or 1, can be expressed as:

$$s_{OOK}(t) = \sum_{k=0}^{\infty} A_k N(t - kT_f), \quad A_k = 1, 0$$

The PPM, which is used for smoothness the UWB spectrum, can be expressed as:

$$s_{PPM}(t) = \sum_{k=-\infty}^{\infty} A_k N(t - kT_f \pm \varphi)$$

where, $\varphi$ is a small shift in pulse position, and here $A_k = 1$.

These various kinds of modulation techniques provide another dimension to the adaptive properties of UWB, for example, UWB might choose BPSK to obtain power efficiency in case of limited available transmit power. In the same way, BPSK may also be a desirable solution if spectral spikes cause a problem to occur due to periodicity of the transmit pulses.

Other modulations like: PPM, PAM, and OOK will perform better over BPSK if cost and complexity of the transceiver is considered. The error probability of M-ary PAM and PPM are shown in Figure 6.5 and 6.6 respectively. When M-ary modulation techniques are applied over both PAM and PPM, PPM shows better performance than PAM as M increases which is illustrated in Figure 6.7.

4.4 RAKE Receiver

UWB channel is highly frequency selective because of large bandwidth. In UWB channel, a vast number of multipath components arrive at the receiver with different time delays that causes bad performance in the receiver. A RAKE receiver can be applied in a multipath fading channel to improve the received signal energy. A RAKE receiver collects the energy in the significant multipath components through any kind of spread spectrum communication system. This receiver combines different signal components that hold propagation behaviour through different channel path [43]. In order to counter the effects of multipath fading, the RAKE receiver uses multiple correlators called fingers. Each finger independently is matched to a single multipath component. The RAKE receiver in UWB systems is much different than narrowband or wideband systems.
IR-UWB RAKE receivers have some drawbacks, firstly, the energy capture for a number of fingers is relatively low when Gaussian pulses are used [44]. Secondly, each multipath pass through different channel causes distortion in the received pulse shape and makes the use of the single LOS path signal suboptimal [44].

Three main types of RAKE receivers are:

- Ideal-RAKE (I-Rake) or All RAKE (A-Rake) receiver: The I-Rake or A-Rake receiver captures all of the received signal power by adjusting the number of fingers equal to the number of multipath components.

- Selective RAKE (S-Rake): The S-Rake combines all the strongest propagation paths with largest value over all the received paths. Implementation of S-Rake requires channel impulse response information.

- Partial RAKE (P-Rake): The P-Rake combines the first arriving multipath components that contain the most of the received signal power. P-Rake requires only synchronization but not full channel estimation.

Figure 6.8 in section 6.3.2, illustrated the BER performance with varying $E_b/N_0$ for different RAKE receivers.

4.5 Underlay and Overlay mode

In the underlay mode, the secondary users should have access to the spectrum bands below the noise floor of the primary users. And in the overlay mode, restrictions are applied on secondary users when they may transmit rather on their transmission power.

The most tempting features of UWB is that it is an underlay system that can coexist in the same spatial, temporal, and spectral domains with other unlicensed or licensed radios. UWB can possibly be implemented both in underlay and overlay modes simultaneously.

As UWB work in the underlay mode because of the very low power level, it is not possible for the unwanted users to detect even the existence of the UWB signals. So it can say that underlay UWB is highly secure in order to exchange information’s. On the other hand, overlay UWB can also be considered as a secure communication if the user’s spread coding or time hopping is known to UWB receiver’s while receiving a user’s information. This is because, direct sequence or time hopping enabled the multiple accesses in overlay IR-UWB.

The amount of transmitted power is the main difference between the two modes. The transmitted power can be much higher in overlay mode and this mode is only applicable in UWB if the UWB transmitter ensures that the targeted spectrum band is completely free of primary users. On the other hand, UWB has a significantly restricted power in underlay mode and because of it, UWB is unlikely to cause any interference to any licensed system. As long as the unlicensed interference remains less than a certain level compared with the licensed,
this underlay transmission in CR will enables the unlicensed (secondary) system to utilize the frequency band of the licensed system. The transmit power in underlay mode must be below 41dBm/MHz as set by the FCC and this means it supports lower data rate. On the other hand, overlay mode supports higher data rate and can transmit with full power.
Chapter 5

UWB based Cognitive Radio

5.1 Introduction

CR and UWB are both already explained in the previous chapter. This chapter will explain the coexistence between CR and UWB. UWB based CR can be use to improve spectrum utilization.

5.2 UWB and Cognitive Radio

UWB has some exceptional capabilities that can help to endowing extra intellective features with CR. Some features of UWB that seems to satisfy the requirements of CR are:

- Negligible interference. UWB can operate in underlay and overlay modes independently or simultaneously with limited transmitted power in underlay mode and high power in overlay mode. This kind of modes causes negligible interference to other communication systems and this characteristics is apparently similar with CR features. CR aimed negligible interference while using licensed frequency band.

- Dynamic spectrum. The nature of short pulses in IR-UWB and its various duration directly interpolates the occupied spectrum.

- Sensing capability. High multipath resolution property helps IR-UWB to properly act as radar, sensing and positioning system. IR-UWB adopts the ability like CR to sense the temporal condition and more precisely it can locate and find the densities of certain substance. For example, in a daily practical life, UWB can scan the road conditions so that it can avoid the traffic collisions. Even also, UWB radar can sense the potholes, dips or bumps on the road.

- Multiple accesses. IR-UWB can adjust the number of chips in a frame to determine the number of users. The state of spectral occupancy is needed in order to adjust the duty cycle in a frame. On the other hand when unused band is explored by CR, the number of free users aims to use this frequency band. So CR should achieve the ability to provide access to multiple users and at the same time, CR systems should need to adopt the technology that is capable to adaptively changing its multiple access parameters.

- Security. UWB provides security both in underlay and overlay mode. But underlay is comparatively more secure because of its very low power level which prohibits other
unwanted user from access. Time hopping and direct sequence provides security in overlay mode. On the other hand, providing security is one of the primary objectives in CR.

5.3 UWB Umbilical Cord

Umbilical cord is a medical term that acts as a bridge to connect a baby in the womb to its mother. This idea can also be introduced in wireless communication systems [42]. The idea of UWB umbilical cord can be used to connect the CR to its surrounding environment to evolve the spectrum occupancy, spectrum positioning, taking information of surrounding remote users, etc. So the umbilical cord must be able to adapt itself with different UWB systems in order to maintain a constant connection to the surrounding world. For this UWB systems must have its own flexible properties and support SDR’s basic reconfigurability principles, though sometimes it’s very hard for UWB to being implemented in SDR mode [42].

Low-data-rate (LDR) and High-data-rate (HDR) systems are calculated as an important feature in UWB and combination of both of these systems make the CR to connect to its environments actively. Low-consumption application and low-cost are handled by LDR system. So these two systems are also responsible for the shape of thickness of umbilical cord in UWB because LDR systems required low speed data transmission to provide all corresponding sensing information and on the other hand HDR system required high speed data transmission [42].

5.4 Implementing CR via IR-UWB

Observing the features of IR-UWB in 4.3.2 and 5.2, it can concluded that IR-UWB can be considered as a suitable candidate to realize UWB based CR. This IR-UWB method utilizes pulse shaped by raised cosine windows or root raised cosine windows has shown in Figure 6.9 [1]. For IR-UWB, it is essential to select the set of utilized pulses carefully for an opportunistic spectrum usage because the pulses transmitted by IR-UWB determine the spectrum occupied. It can be assumed that whether spectrum opportunities are available or not can be determine through the spectrum sensing performance. This raised cosine or root raised cosine windows can lead to a very efficient spectrum usages because it (i) can mitigate intersymbol interference (ISI), (ii) has sharp fall-offs and inhibited side lobes in the frequency domain [1] (iii) frequency response consists of unity gain at low frequencies (iv) have a pulse width and bandwidth that can be controlled simultaneously [1].
Cognitive radio chooses the raised cosine windows because it is suitable for spectrum opportunities agreeing with available bandwidth and data rate needed. To determine the spectrum sensing performance, center frequency and bandwidth is needed where separate selected pulses are mixed with a locally generated cosine signal at the center frequency of spectrum opportunity and then taking the sum of all these selected pulses gives the final pulse shape. Considering all of these including spectrum properties of the raised cosine windows, it can assume that information of all these spectral properties are available in CR’s memory and CR device are also expected to need the facility and ability to allow users to load information so that it can be recalled and processed the loaded information’s when needed [1]. It is noted that a higher roll-off raised cosine window is required to fulfil the higher percentage of white space [1].

So from the above discussion, in the case of the raised cosine windowing based method, IR-UWB can be a suitable method for CR.

5.5 Reducing Interference of UWB via Cognitive Radio

In UWB signals, FCC’s spectral mask, showed in Figure 4.1(a), helps to control the interference of the spectrum users and although this interference will be very unlikely because most UWB devices will work in indoor basis. Even if there remains any free band that are not used by any other devices within the same spectrum, the FCC’s spectral mask expects UWB to avoid sending a signal in that specific band. In the case of outdoors, UWB will create interference to primary users at the same band. Two kinds of UWB interference can be observed in the WPAN environment, one is occurs to licensed users at the same band and another mutual interference occurs among unlicensed users. So, to overcome from these kinds of interference, CR will be well matched for UWB applications. Because the nature of CR with UWB will help to mitigate these kinds of interference.

5.6 Channel Detection Capability of CR via RAKE receiver

In [45], a UWB Rake receiver is designed to increase the significant BER performance in order to achieve multipath diversity. The authors showed the performance of CR in a cross-layer UWB receiver architecture where it exchanges information with the physical layer for probable channel conditions before allocating links dynamically for its data transmission. A RAKE receiver is introduced in the UWB receiver to collect energy from different propagating multipaths that improves the overall performance. The CR in [45], divides the proposed UWB receiver band into narrow sub-bands or channels so that it can scans each of these sub-bands and detects them as “free” channels based on interference temperature. The CR can detect the “free” channels with the help of a RAKE receiver through the given
proposed procedure and then saves the “free” channels in a “channel pool” using the first-in-first-out (FIFO) technique.
Chapter 6

Results and Interpretation

6.1 Introduction

This chapter describes some simulation results that have been categorized into three categories:

1. a) Spectrum sensing detection.
   b) Multitaper spectrum estimation.
2. a) Symbol error probability for UWB Modulation, and
   b) Performance comparison of different RAKE receivers.
3. Pulse shaped IR-UWB in CR.

The first steps contain the spectrum sensing detection based on different data sample in order to find out the fixed length decision rule. Multitaper spectrum, which is a reliable, accurate and real-time method in order to detect the unused available spectrum bands, has been investigated as well. The coherence of the multitaper method and the properties of DPSS window have also been compared with other window methods.

The second steps investigated the performance of UWB modulation techniques and UWB RAKE receivers.

The third steps investigated the IR-UWB that has some impressive characteristics in short-range communication system and also shows that the strong relation between the objective of CR and features of IR_UWB system.

6.2 Spectrum sensing

6.2.1 Spectrum sensing detection

In section 3.2.2, this paper has already explained the equation of probability of false alarm ($P_F$) and probability of detection ($P_D$) as:

$$P_F = P_r (D > \lambda | H_0) = 1 - \Gamma (N, \frac{\lambda}{\sigma_w^2})$$

$$P_D = P_r (D > \lambda | H_1) = 1 - \Gamma (N, \frac{\lambda}{\sigma_\xi^2 + \sigma_w^2})$$

$$\Gamma(N, a) = \frac{1}{\Gamma(a)} \int_0^N e^{-t} t^{a-1} dt$$
Where, $\Gamma(x, y)$ and $\Gamma(x)$ are incomplete and complete gamma functions respectively.

![Figure 6.1- The probability of detection for different data samples N.](image)

The Figure 6.1 shows the probability of detection for different number of data samples N. Consider the signal is a White Gaussian with mean=0 and variance=1. This figure shows that about 40 sample data are needed to find out the fixed length decision rule.

6.2.2 Multitaper Spectrum

Figure 6.2(a) shows that the Fourier transform of spectral coherence gives complex values with each having a magnitude and phase of their own. This Figure also shows the general magnitude squared coherence pairs between 0.15 and 0.7. The reasonable coherence is seen in lower panels when slepian tapers is eight and the number of windows are 4.5, i.e. NW=4.5. Figure 6.2(b) shows the percentage of the significant coherence frequency greater than or equal to 95% within this band for each data set. Here, mean = 0.29 and the estimated coherence is 2.5% above the 95% confidence level.
In section 3.2.3, this paper has already explained one of the important properties of the Slepian sequence, originally known as discrete prolate spheroidal sequences (DPSS), is that the Fourier transform of a Slepian sequence or window gives maximum energy density inside
a given bandwidth under a finite sample-size constraint. Figure 6.3 and 6.4 shows that only Slepian window satisfy this property and there is no other window in the signal processing area that can fulfil this requirement [48].

![Figure 6.3- Comparison of DPSS and Kaiser window transforms.](image-url)
Figure 6.4- Comparison of DPSS, Hamming and Tukey window transforms.

In Figure 6.3, DPSS window has slightly narrower main lobe and in Figure 6.4, though the resolution of hamming and tukey is better but DPSS has less spectral leakage. The DPSS window allows focusing the maximum energy in the main lobe of the frequency response. Also DPSS window has lower overall side-lobe levels and better overall specifications. The length of the window in this case is 64.

6.3 UWB

6.3.1 Symbol error probability for UWB Modulation

Pulse Amplitude Modulation (PAM), Pulse Position Modulation (PPM) and On-Off Keying (OOK) has been mentioned as a modulation suitable to UWB communication over binary phase shift keying (BPSK) if cost and complexity of the transceiver is considered.

The probability of symbol error, \( P_e \), for M-ary PAM is simply obtained by

\[
P_e = \left(1 - \frac{1}{M}\right) \text{erfc}(y)
\]

where

\[
y = \sqrt{\frac{E_b}{N_0} \frac{3 \log_2 M}{M^2 - 1}}
\]

Similarly, for M-ary PPM,
The error probability of M-ary PAM and PPM are shown in Figure 6.5 and 6.6 respectively. When M-ary modulation techniques are applied over both PAM and PPM, the performance of PAM increases when M decreases, meanwhile, the performance of PPM increases when M increases. The results of Figure 6.5 and 6.6 shows that:

For PAM, the better performance can be obtained at $\frac{E_b}{N_0} \approx 11\text{dB}$ when BER= $10^{-3}$ and M= 4.

Similarly, For PPM, the better performance can be obtained at $\frac{E_b}{N_0} \approx 6.2\text{dB}$ when BER= $10^{-3}$ and M= 32.

![Figure 6.5- Error probability of M-ary PAM signal.](image)
Figure 6.6- Error probability of M-ary PPM signal.

Figure 6.7- Error probability for M-ary PAM and M-ary PPM signals.

Figure 6.7 shows the performance results between PAM and PPM UWB systems. This shows that PPM achieved a significant better performance when M increases, i.e., PPM has better performance than PAM as M increases.
6.3.2 Rake receiver

The RAKE receiver can improve the multipath fading channel's received signal energy. Rake receiver uses multiple correlator called fingers in order to counter the effect of multipath fading channel. Figure 6.8 illustrates the BER performance varying the values of $E_b/N_0$ for different RAKE receivers. The figures clearly show that the performance of single-path S-Rake is better than single-path P-Rake because single-path S-Rake uses the strongest propagation path.
6.4 Pulse Shaped IR-UWB in CR

As this paper has already explained in section 5.4, IR-UWB can employ pulse generated cosine windows to usage available spectrum efficiently and this raised cosine windowing method can be a convenient way for IR-UWB of realizing CR. Raised cosine with higher roll-off filters can be used in cognitive radio in order to filling the higher percentage of white space. Raised cosine or root raised cosine functions used in communication systems to avoid intersymbol interference.

Different pulse shapes and spectra of raised cosine windows or root raised cosine windows are illustrated in Figure 6.9. Section 5.4 demonstrates that pulse shaped satisfies some properties that has some similarities with CR like: (i) can mitigate intersymbol interference (ISI), (ii) has sharp fall-offs and inhibited side lobes in frequency domain, (iii) frequency response consists of unity gain at low frequencies.
Figure 6. 9- Different pulse shapes and spectra of Raised cosine windows and Root raised cosine windows with different roll-off factors $\alpha=0.3$, $\alpha=0.5$ and $\alpha=0.9$. 
Chapter 7

Conclusion

The CR is a promising and effective technology used to overcome the rising crisis of spectrum availability at frequencies and allow the unlicensed users to access licensed spectrum. The combination of UWB and CR would be a exciting revolutionary technology to offer a new approaches to the spectrum usage.

CR uses different kinds of sensing methods to avoid interference with the PU. The multitaper method (MTM), which is also a kind of sensing method and is designed to work with very low sample data for analysing the transient or nonstationary signals, has been investigated in this thesis paper. The examples in section 6 have demonstrated that any reasonable coherence of the multitaper processor can reliably detect at lower panels. Less spectral leakage and the better frequency resolution with higher variance can be achieved by reducing the windows value. Also the Fourier transform of DPSS window gives maximum energy density with narrower main lobe and less spectral leakage. Meanwhile this property of DPSS is compared with other window methods and shows that no other window in signal processing can satisfy this property, though hamming and tukey method has narrower main lobe and better resolution compared with DPSS but DPSS has less spectral leakage.

A RAKE receiver have also introduced in UWB system in order to improve received signal energy and collect the available rich multipath diversity. Taking a consideration of BER performance for varying the values of $E_b/N_0$ in case of RAKE receivers, this paper has shown that S-Rake has better performance compared with P-Rake receiver depending on the number of fingers.

UWB is used to give the CR accompany to be the best choice in short range systems. IR-UWB shows some impressive characteristics in short-range communication system with a variety of throughput options including high-data-rates. The strong synergy between the aims of CR and features of IR-UWB has been shown in this thesis through the raised cosine windowing method because raised cosine window method is a convenient way of IR-UWB of realizing CR. In the future, UWB based CR will be a role model in short range systems.
References


