SPECTRUM SENSING AND DETECTION FOR
COGNITIVE RADIO SYSTEM

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Spectrum Sensing and Detection for Cognitive Radio System

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DEDICATION

This thesis is a dedication to my family and friends.
ABSTRACT OF THE THESIS

Spectrum Sensing and Detection for Cognitive Radio System
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Statistics have proved that more than 70% of the radio spectrum is not used efficiently due to fixed spectrum allocation policies. More often, considerable portion of the allocated spectrum is used intermittently with variations in effective utilization being 20% to 80%. Clearly the regulatory process of ensuring the optimal use of the spectrum needs to be flexible and responsive in order to adhere to changes in technologies, demand markets and public policy. Essentially every wireless carrier subscribes its own license to avoid interference and for new technologies, find difficult to operate in their spectra because these are already occupied by commercial vendors, operators, contractors and the government. In any case, it is difficult to reclaim and release spectrum bands already licensed, so a new dynamic policy of spectrum allocation can be employed.

In this paper, we present an effective strategy of spectrum estimation like those of the Periodogram, Welch Spectrum Estimation and Overlap Window Averaged Spectrum Estimation and present the architecture of the optimal Spectral Estimator using Polyphase Filter Banks for Cognitive Radio. In this context, a number of Primary Signals (Licensed Users), Secondary Signals (Unlicensed Users) of different SNR and different Carrier frequencies are made to occupy a wide frequency band. The designed Cognitive radio intelligently scans the entire frequency spectrum and searches for spectrum holes, the vacant bands where a potential secondary User can access the band without causing significant interference to the Primary Users.
TABLE OF CONTENTS

ABSTRACT ....................................................................................................................................... v
LIST OF FIGURES ........................................................................................................................ vii
ACKNOWLEDGEMENTS ............................................................................................................... ix
CHAPTER
  1 INTRODUCTION ...................................................................................................................... 1
    1.1 Characteristics of Cognitive Radios .................................................................................. 2
    1.2 Cognitive Capability ......................................................................................................... 2
    1.3 Reconfigurability ............................................................................................................... 3
  2 COGNITIVE RADIO ARCHITECTURE ........................................................................ 4
  3 LITERATURE REVIEW .......................................................................................................... 10
    3.1 Stepwise Approach to Spectrum Sensing ...................................................................... 10
    3.2 Classification of Techniques ......................................................................................... 10
    3.3 Transmitter Detection ..................................................................................................... 11
    3.4 Energy Detection ............................................................................................................ 16
  4 PROPOSED IMPLEMENTATION .................................................................................. 24
    4.1 Cyclostationary Detection and its Proposed Variations .................................................. 24
    4.2 Spectral Line Generation ............................................................................................... 24
    4.3 Channelizers ................................................................................................................... 27
    4.4 Implementation of 40 Channel Channelizer .................................................................... 31
    4.5 Effect of Band-Edge Filtering ......................................................................................... 34
    4.6 Conclusion ....................................................................................................................... 37
BIBLIOGRAPHY .......................................................................................................................... 38
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Dynamic changes in all layers.</td>
<td>2</td>
</tr>
<tr>
<td>2.1</td>
<td>Depiction of spectrum hole and the occupied bands.</td>
<td>4</td>
</tr>
<tr>
<td>2.2</td>
<td>Concept of cognitive based on multiple systems.</td>
<td>8</td>
</tr>
<tr>
<td>3.1</td>
<td>Cognitive radio system modularization diagram.</td>
<td>10</td>
</tr>
<tr>
<td>3.2</td>
<td>Classification of spectrum detection techniques.</td>
<td>11</td>
</tr>
<tr>
<td>3.3</td>
<td>Block diagram of matched filter.</td>
<td>12</td>
</tr>
<tr>
<td>3.4</td>
<td>Input constellation diagram.</td>
<td>12</td>
</tr>
<tr>
<td>3.5</td>
<td>Impulse response and frequency response of the Sqrt Nyquist filter.</td>
<td>13</td>
</tr>
<tr>
<td>3.6</td>
<td>Single modulated spectrum and composite modulated spectrum.</td>
<td>14</td>
</tr>
<tr>
<td>3.7</td>
<td>Composite spectra with/without noise.</td>
<td>15</td>
</tr>
<tr>
<td>3.8</td>
<td>Constellation diagram before and after matched filter for good SNR condition.</td>
<td>16</td>
</tr>
<tr>
<td>3.9</td>
<td>Frequency response before and after matched filter for good SNR.</td>
<td>17</td>
</tr>
<tr>
<td>3.10</td>
<td>Constellation diagram before and after matched filter for medium SNR.</td>
<td>18</td>
</tr>
<tr>
<td>3.11</td>
<td>Frequency response at the input and output of the matched filter (for medium SNR).</td>
<td>19</td>
</tr>
<tr>
<td>3.12</td>
<td>Constellation diagram before and after matched filter for low SNR.</td>
<td>20</td>
</tr>
<tr>
<td>3.13</td>
<td>Frequency response output of matched filter.</td>
<td>21</td>
</tr>
<tr>
<td>3.14</td>
<td>Block diagram for energy detector.</td>
<td>21</td>
</tr>
<tr>
<td>3.15</td>
<td>Spectral leakage of the rectangular window.</td>
<td>22</td>
</tr>
<tr>
<td>3.16</td>
<td>Frequency response of the Kaiser window with main lobe width $\alpha = 3\pi$ (inside, impulse response of the Kaiser window).</td>
<td>23</td>
</tr>
<tr>
<td>3.17</td>
<td>Spectrum of single windowed FFT and averaged windowed FFTs.</td>
<td>23</td>
</tr>
<tr>
<td>4.1</td>
<td>Depiction of spectral lines.</td>
<td>25</td>
</tr>
<tr>
<td>4.2</td>
<td>Frequency response. (Top) Typical cyclostationary product. (Bottom) Time delayed cyclostationary product.</td>
<td>26</td>
</tr>
<tr>
<td>4.3</td>
<td>Second variation: Frequency response of the cyclostationary product (product of x (n) with its filtered derivative conjugate).</td>
<td>27</td>
</tr>
</tbody>
</table>
Figure 4.4. Impulse response and frequency response of the frequency shifted band edge filter ....................................................................................................................28

Figure 4.5. Third variation: Cyclostationary BE product .......................................................................................................................29

Figure 4.6. Polyphase channelizer with folded window ......................................................................................................................29

Figure 4.7. Multiple instantiation of the prototype filter capturing different bands (channels) ....................................................................................................................30

Figure 4.8. Display of channels 1-5 in time domain and their individual spectra without noise ...............................................................................................................31

Figure 4.9. Composite time signal and its spectra without noise .......................................................................................................................32

Figure 4.10. Composite spectra with/without noise (high SNR condition) .................................................................................................32

Figure 4.11. Composite spectra with/without noise (low SNR condition) .................................................................................................33

Figure 4.12. Spectra of individual channels without averaging (high SNR, easily detectable) ...................................................................................................................33

Figure 4.13. Spectra of individual channels without averaging (low SNR, hardly detectable) ...................................................................................................................34

Figure 4.14. Spectra of the individual channels for high SNR with averaging (very easily detectable) ........................................................................................................35

Figure 4.15. Spectra of the individual channels for low SNR with averaging (detectable) ...................................................................................................................35

Figure 4.16. Band edged spectra of the channels after averaging (for good SNR condition) ......................................................................................................................36

Figure 4.17. Band edged spectra of the channels after averaging (for low SNR condition) ......................................................................................................................36
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CHAPTER 1

INTRODUCTION

Federal Communications Commission (FCC) is responsible for regulation of state-wide telecommunication, management and licensing of the radio spectrum within the United States and it enforces requirements on inter-state interference in all frequency bands. They license chunks of the radio spectrum to particular geographic areas [1]. This has left with very few unlicensed bands left open for use as long as they followed certain power regulations. Moreover, with the recent surge in usage of personal wireless technologies, these unlicensed frequencies have become crowded ranging from wireless carriers to TV broadcasting stations [2].

In order to solve the problem of over-crowding, FCC has been designing ways to efficiently manage radio resources. The basic idea is to let people use licensed frequencies, provided they can guarantee interference from the primary Users will be minimal.

Cognitive Radio can smartly sense, detect and adapt to the changing environment by altering its transmission parameters. Cognitive Radio is based on the software defined Radio (SDR) in which all transmission parameters change like SDR but it will also change the parameters according to the spectrum availability [3], [4]. SDR is a radio or can be termed as software turnaround that includes the transmitter in which the operating parameters including the transmission range, modulation type or maximum radiated or conducted output power can be altered by making the change in software without making any changes in hardware [5], [6]. SDR is used to minimize hardware requirements, it gives user a cheaper and reliable solution. But will not take into account spectrum availability.

A dynamic spectrum access methodology allows the cognitive radio to operate in the best available channel [5]. More specifically the cognitive radio technology will enable the user to determine which portion of the spectrum is available, detect the presence of primary user (spectrum sensing), select the best available channel (spectrum management), coordinates the access to the channel with other users (spectrum sharing) and migrate to some other channel whenever the primary user is detected (spectrum mobility) [5].
1.1 Characteristics of Cognitive Radios

Cognitive Radio dynamically selects the frequency of operation and adjusts its transmission parameters depending upon the Radio Access Technology as pictured in Figure 1.1. The main characteristics are Cognitive Capabilities and Reconfigurability.

![Dynamic Spectrum Allocation Diagram]

**Figure 1.1. Dynamic changes in all layers.**

1.2 Cognitive Capability

Cognitive Capability refers to the ability of radio to sniff or sense information from its environment and perform real-time post processing on it. The cognitive capability can be characterized by three parameters: Spectrum Sensing, Spectrum Analysis and Spectrum Decision [5].

The spectrum sensing performs the role of monitoring and detection of spectrum holes. The spectrum analysis will estimate the properties of the characterized spectrum hole. In the spectrum decision, the appropriate spectrum is selected to determine parameters like data rate, transmission mode, etc.
1.3 RECONFIGURABILITY

Reconfigurability refers to the ability of radio that allows the cognitive radio to adjust its parameters like link quality, operating frequency, modulation and transmission power at run time without any modifications in the hardware components.
CHAPTER 2
COGNITIVE RADIO ARCHITECTURE

The cognitive radio allows the occupancy of temporally unoccupied spectrum, which is termed as spectrum hole as depicted in Figure 2.1 or white space [3]. If the particular channel is occupied by a licensed user, the cognitive radio capable device moves to another spectrum hole or stays in the same channel, varying its transmission power or modulation scheme to avoid interference.

Figure 2.1. Depiction of spectrum hole and the occupied bands.

The main interest in the TV bands is driven by the worldwide switchover from analogue to digital terrestrial TV which will release a large portion of spectrum known as the digital dividend and might also make available the guard bands between existing or new broadcasting channels (the so-called TV White Spaces or TVWS) available for opportunistic use [6]. These frequency bands are valuable as they provide propagation characteristics that enable signals to penetrate thick walls and travel long distances. The general consensus worldwide is that at least part of this digital dividend and TVWS spectrum should be allocated for mobile broadband services [5]. The debate on these so-called white spaces, is regularly grabbing headlines in the media with a noticeable interest from and role for new
players in the wireless field. The debates centers on the free use of White Space Devices (WSD), i.e. devices that could opportunistically make use of free spectrum for various goals. Parties in favor of these devices see major opportunities for the freed up spectrum, including more mobile broadband services, offering better quality of service, to more users [5]. Traditional users of the freed-up spectrum bands and adjacent spectrum bands such as broadcasters are concerned about the consequences of this type of unlicensed use that could interfere with licensed use. They demand a highly regulated approach [1]. In the US, the FCC adopted rules for unlicensed use of television white spaces already in 2008. This announcement was a major endorsement for Cognitive Radio and will softly introduce spectrum sensing technologies in the market in the coming years [7]. The FCC has proposed to use geo-location technology as a primary measure to combat interference: i.e. to check in a database whether a certain frequency band is available or not at a certain location before authorizing the unlicensed use [6]. However, the FCC also stipulates that the geo-location based devices should be complemented with sensing technology: [6] The Commission also has required that devices include the ability to listen to the airwaves to sense wireless microphones as an additional measure of protection for these devices. To implement reuse of the TV white spaces, from a platform point of view, the main challenges are related to the sensing requirements. Indeed it is impossible to sense the exact impact of the secondary transmitter on the primary receiver that should be protected. The IEEE 802.22 Working Group (WG) was formed in November 2004, after the FCC released its Notice of Proposed Rule Making (NPRM) for the TV bands in May 2004. This WG was specifying an air interface (including PHY and MAC specifications) for Wireless Regional Area Networks (WRAN) to coexist with legacy TV transmission relying on cognitive capability [1]. It was the first standard designed for opportunistic spectrum access [5]. It is only possible to sense the channel from the primary transmitter to the secondary transmitter and huge safety margins are added in order to accommodate unknown blocking to the sensed channel. Indeed, if the sensed channel would be blocked, the primary transmitter would seem to be further away than it actually is and the secondary transmitter could falsely assume that the channel is free [1]. For the TV white spaces, sensing up to -116 dBm is hence targeted, which is well below the noise floor in those bands [2]. The FCC’s conclusion however stated that devices do not consistently sense TV or wireless microphone signals and the transmitter is
capable of causing interference to these signals [1]. The 802.22 networks operate in a fixed point-to-multi-point topology where a Base Station (BS) controls a cell consisting of a number of Consumer Premise Equipment (CPEs). The BS is an entity installed by an operator and controls the cell strictly. Next to more traditional medium access control, that addresses when to transmit, it decides on how CPEs should access the spectrum [5]. Moreover, the BS maintains control of a distributed sensing strategy to keep track of potential primary users (TV or wireless microphone signals). Clearly, it is possible to have multiple 802.22 cells that interfere. This is aggravated because of the very large transmission area of those systems. Coexistence issues of 802.22 cells are hence also addressed in the 802.22 standard [6].

One of the important components of the IEEE 802.22 document to achieve the required cognitive capability is related to spectrum measurements. The spectrum measurement in 802.22 is primarily based on transmitter detection [7]. In order to check the presence of primary signals, 802.22 devices need to be able to detect signals at very low Signal-to-Noise Ratio (SNR) levels [4], [8]. Since the detection is done at low SNR, it is assumed that the detection of TV signals is done in a non-coherent manner, which means that no synchronization is needed. The required accuracy of the spectrum sensing, the frequency band and time period, is determined in a centralized way by the BS. Using the local measurements, the BS can establish a spectrum occupancy map [2]. The BS does not require the same sensing accuracy of each CPE and algorithms to optimize or distribute the sensing load across CPEs can be used. To optimize the sensing, 802.22 devices are supposed to be equipped with a dedicated Omni-directional antenna for sensing [6]. This is in addition to a directional antenna which is used for data transmission in the target direction, minimizing the interference area. To be able to optimize the sensing accuracy of the Omni-directional antenna, it would most likely have to be mounted outdoors. 802.22 devices can be instructed to perform in-band or out-of-band sensing, where a band denotes the TV band currently used by the cell. For in-band sensing, the 802.22 communication needs to be temporarily halted, in order not to interfere with the sensing [6]. There clearly is a trade-off between speed, at which a primary TV signal can be detected and the efficiency or throughput achieved by the 802.22 cell. To avoid too frequent long connectivity halts, a two-phase sensing mechanism is used [6].
Fast sensing, i.e. based on a simple and fast sensing technique, is performed more frequently. After one (or more) fast sensing periods, the BS can decide whether to perform a fine sensing. This fine sensing takes more time but should in fact only be carried out if the fast sensing results are not sufficient to draw conclusions [2]. Given the fact that TV signals do not come on the air frequently, this two-phase sensing method proves highly effective. If multiple 802.22 cells operate in the same area, it is required that their sensing strategy is synchronized (i.e., they should halt communication when other cells sense). Since coexistence among different 802.22 cells is an important issue, such synchronization is embedded in the 802.22 standard [6]. Contrary to the TV signals detection, sensing of wireless microphone transmissions is much harder as these transmit at a much lower power and occupy much lower bandwidths. Therefore, in addition to transmitter detection, a second sensing option is enabled in the 802.22 standards. This second option relies on the transmission of beacons by the microphones themselves or a special device carried by microphone operators. This primary network information monitoring is embedded in the 802.22 MAC [1]. The exact sensing algorithms to be used during the fine and fast sensing periods are not standardized, but an extensive list is provided as annex to the standard. There are two trends in cognitive radio; one trend is the so-called Multiple Systems and which switches wireless communication systems according to the radio conditions. The other trend is the so-called Dynamic Spectrum Access, which recognizes spare frequencies of a primary system and allocates them to be used for communication of a secondary system to such an extent that the primary system would not be affected. From a terminal point of view, SDR (Software Defined Radio) terminals that support multiple wireless systems have been proposed [2], [5] and [6]. Mobile terminals can measure radio information and report that to the base station and the base station decides whether to switch to other systems according to this report from the mobile terminal. However, that is not sufficient for maximizing system capacity and satisfying requirements for user communication quality because system load and information that can be acquired from the network (e.g. the number of terminals that connect to an access point) are not taken in account [1].

For example, we assume we can communicate with three systems: A, B and C as shown in Figure 2.2. When the current time is t2, cognitive terminal (CT) D communicates using the frequency of System A and when the current time becomes t3, terminal D changes
Figure 2.2. Concept of cognitive based on multiple systems.

The wireless communication system from System A to System B to communicate using the frequency of System B. As the number of wireless communication systems used simultaneously is not limited to one and the cognitive system can transmit and receive data with multiple wireless communication systems simultaneously. Furthermore, terminals of the cognitive radio system (cognitive terminal) switch the wireless communication system frequently according to the radio conditions as stated. Therefore, in cognitive radio, the corresponding node need not know which wireless system is being used. Based on this concept, two requirements to achieve cognitive radio are as below:

1. System architecture for fast system handover, which can reflect radio environments that change dynamically and system load and information that can be acquired from the network [6].

2. Assignment of one local IP address to the terminal regardless of the number of wireless communication systems that the terminal communicates with. Provided that EV-DO (cdma2000 1x Evolution Data Optimized) is system A, LTE (Long Term Evolution) is system B and wireless LAN is system C, terminal D can communicate with EV-DO, wireless LAN and LTE adaptively according to the radio conditions. However, terminal D can use different radio systems only when terminal D is located in the area where EV-DO, LTE and wireless LAN are in service [6]. The service areas of each system differ from each other due to the difference in frequency performance and difference in service (carrier, bit rate and charge, for example), it is
on this basis that the architecture of the cognitive base station has to be considered.
When we set up a cognitive BS (Base Station) that supports multiple wireless systems
like that shown below, only the center area of the base station, which is covered by all
kinds of wireless communication systems, can satisfy the conditions. This
architecture is simple and easy to construct; however, an area where cognitive radio
can be adopted is narrow and limited [5]. Actually, LTE access points are not always
located in the same place where EV-DO access points are located; therefore, this
architecture is not suitable and it would seem that the realization probability of the
architecture is low. To expand the area that satisfies the conditions the cognitive base
station can be described as below:

1. The area of the cognitive base station is equivalent to the area in which access
   points of a cellular system are covered, which is the widest area among the access
   points of other wireless systems.

2. A cognitive base station has the function of access points of a cellular system, the
   function of access points of LTE and wireless LAN in the cognitive base station
   area and a control node to integrate these functions. The concept of a cognitive
   BS (base station) based on this definition is shown below.

   Actually, LTE access points are not always located in the same place where the
   EV-DO access point is located; therefore, this architecture is more realistic. Moreover,
   placing a control node inside the cognitive base station is one characteristic. The control node
   controls these systems below the IP layer. Thus, converging multiple access points of
   multiple systems inside the cognitive base station enables us to treat the radio resources
   spread throughout the cognitive base station area as an internal radio resource of the
   cognitive base station. Consequently, that is expected to achieve fast system handover.
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EV-DO access point is located; therefore, this architecture is more realistic. Moreover,
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CHAPTER 3

LITERATURE REVIEW

This chapter includes the summary of various approaches employed to address the problem of Spectrum Sensing. The chapter encompasses the background work on spectrum sensing techniques.

3.1 STEPWISE APPROACH TO SPECTRUM SENSING

The System is sub-divided into different modules as shown in Figure 3.1. The primary input to the system module is the primary User’s waveform from Primary User. The modules forming the entire system include: Primary Users Waveform, Processing on Waveform, Detection of Waveform and Feature Extraction and Classification [5].

![Figure 3.1. Cognitive radio system modularization diagram.](image)

3.2 CLASSIFICATION OF TECHNIQUES

The main challenge to the Cognitive radios is the spectrum sensing. In spectrum sensing there is a need to find spectrum holes in the radio environment for CR users. However it is difficult for CR to have a direct measurement of channel between primary transmitter and receiver [5].
A CR cannot transmit and detect the radio environment simultaneously, thus, we need such spectrum sensing techniques that take less time for sensing the radio environment [3].

In literature, the classification of Spectrum Sensing Techniques is shown in Figure 3.2.

![Figure 3.2. Classification of spectrum detection techniques.](image)

### 3.3 Transmitter Detection

Transmitter Detection involves sensing primary Signals that are transmitting at any given time. Now in the following section we will discuss each of the transmitter detection techniques their pros and their cons.

Figure 3.3 depicts the block diagram of matched filter. Let \( s(t) \) be the received modulated signal and \( n(t) \) be the additive white Gaussian Noise in the channel. The signal received by CR is input to matched filter which is \( r(t) = s(t) + n(t) \). The matched filter convolves the \( r(t) \) with \( h(t) \) where \( h(t) = s(T-t + \tau) \). Finally the output of matched filter is compared with a threshold \( \lambda \) to decide whether the primary user is present or not. Matched filter is a linear filter designed to provide the maximum signal-to noise ratio at \( t \) [7].

A Matched filter is an optimal detector in an AWGN channel if the waveform of the Primary user is previously known by CR [7]. It means that CR should have knowledge about the waveform of primary user such as modulation type and order, symbol rate, the pulse shape and the packet format. So if CR doesn’t have this type of prior information then it is difficult to detect the primary user [9].
Block Diagram of Matched Filter Technique is explained in detail with its implementation.

Step 1: Consider an input 16-QAM signal with its Constellation diagram in Figure 3.4.

Step 2: This Input 16-QAM signal is passed through a Transmitter Pulse-Shaping filter called the Raised Cosine Filter shown in Figure 3.5.
Typically a digital communication system involving band-limited signals along with additive white noise normally implemented with the pulse-shaping filter at the transmitter side and a corresponding Matched Filter at the receiver side. These filters execute important functions

- They ensure the receiver’s sampling process is bestowed with Nyquist Spectrum, thereby considerably reducing inter-symbol interference.
- They also improve the SNR of the signal affected by additive white Gaussian Noise (AWGN).

The spectrum of a standard Nyquist pulse with T-second spacing between zero crossings is an ideal low-pass response convolved with the transform of any even symmetric window function which limits the time extent of the pulse. The spectral window function is usually a raised cosine of support $\beta/T$ (with $0<\beta<1$) and the resultant spectrum is called a Raised Cosine Nyquist filter with $\beta\%$ rolloff. A common roll-off factor is usually 0.4, but systems have been designed with $\beta$s less than 0.2 and as large as 1.0. The impulse response
and the frequency response is shown below. The ratio of input sampling frequency to the filter sampling frequency is 1:4.

Step 3: Next, a modulated Single Spectrum is obtained as shown in Figure 3.6. In a similar manner, we generate a Composite Modulated Spectra consisting of different Signals of varying Signal to Noise Ratio (SNR) as shown in the Figure 3.6.

Figure 3.6. Single modulated spectrum and composite modulated spectrum.

Step 4: The Composite Modulated Spectra is passed through a Noisy Channel. The noise components distort the existing signals and also occupy regions of the spectra as depicted in Figure 3.7.

Step 5: Next we implement the Matched Filter on the Composite Spectra detecting the band of interest. The technique is examined for three different SNR scenarios.

From the Constellation Diagram in Figure 3.8 for the High SNR condition, we notice the symbol points are closely stacked together and easily identifiable after the Matched Filter. There is hardly any inter-symbol interference as shown in Figure 3.8.
Figure 3.7. Composite spectra with/without noise.

Also from the Frequency Response shown in Figure 3.9 for the high SNR condition; one can easily identify the center frequency and bandwidth of the Signal even before implementing the Matched Filter.

Step 6: Next, we examine the Constellation Diagram for medium SNR after the Matched Filter. As we observe, there is moderate inter-symbol interference because of the dispersing of the symbol points. However, one could still identify the 16 symbols even after affected by noise as shown in Figure 3.10.

The Corresponding Frequency Response for medium SNR is shown in Figure 3.11. In this case too, one could determine the center frequency and bandwidth of the signal assuming it is not noise like.

Step 7: Here, we implement the Matched Filter for the Low SNR condition. As shown in Figure 3.12, the symbol points are highly dispersed in the constellation space causing high inter-symbol interference.
Figure 3.8. Constellation diagram before and after matched filter for good SNR condition.

Also shown are the Frequency Response before and After Matched Filter for the Low SNR condition.

We notice the Matched filter detects the center frequency and bandwidth of Noise like signal as shown in Figure 3.13.

Thus for low SNR signals, Matched Filter fails to detect the signal as like most other Post detection techniques. Another drawback is the Matched filter detects only a particular waveform whose prior information is known. However if there exists a number of modulated signals of different characteristics occupying the wide-band, a similar number of Matched Filters would be required to demodulate corresponding waveforms thereby increasing the complexity of the Cognitive Radio Receiver.

3.4 ENERGY DETECTION

If CR can not have sufficient information about primary user’s waveform, then the matched filter is not the optimal choice. However if it is aware of the power of the random
Gaussian noise, then energy detector is optimal [5]. In [8] the authors proposed the energy detector as shown in Figure 3.14.

One approach to simplify matched filtering approach is to perform non-coherent detection through energy detection. This sub-optimal technique has been extensively used in Radiometry [7]. An energy detector can be implemented similar to a spectrum analyzer which is based on the Welch Method.

Welch method is the use of improved estimates of the average periodogram estimate of the power spectrum of random signals; it uses the signal segment overlap, windowing, FFT techniques to calculate the power spectrum. Compared with the periodogram, Welch spectrum estimation methods can improve the smoothness of the curve and greatly improve the resolution of spectral estimates.

The DFT performs a finite sum and as such processes data sequences collected over finite intervals traditionally described as being of length N samples. The collection of N samples from the time (or index) line has the effect of applying a gating or windowing function to the collected data.
First, the window widens the signal’s spectral width from infinitesimally small to the main lobe of the \( \sin(\pi f NT)/(\pi f NT) \) and second, spectral leakage smears or leaks the spectrum through the \( \sin(\pi f NT)/(\pi f NT) \) side-lobes to remote spectral regions far removed from the spectral location of the un-windowed spectrum.

Also if we notice the rectangular window shown in Figure 3.15, the side-lobe structure of the windowed transform limits the ability of the transform to detect spectral components of significantly lower amplitude in the presence of a large amplitude component while the main-lobe width of the windowed transform limits the ability of the transform to resolve or separate nearby spectral components.

The high side lobe levels of the rectangle window are due to the abrupt discontinuity at the boundary edges. We reduce side lobes by reducing the severity of the boundary discontinuities as in the Kaiser window. A good window is an even symmetric weighting...
Figure 3.11. Frequency response at the input and output of the matched filter (for medium SNR).

function that smoothly and gently transitions from near zero levels at the boundaries to unity amplitude at its center.

The side-lobe structure of the windowed transform limits the ability of the transform to detect spectral components of significantly lower amplitude in the presence of a large amplitude component while the main-lobe width of the windowed transform limits the ability of the transform to resolve or separate nearby spectral components.

The high side lobe levels of the rectangle window are due to the abrupt discontinuity at the boundary edges. We reduce side lobes by reducing the severity of the boundary discontinuities. A good window is an even symmetric weighting function that smoothly and gently transitions from near zero levels at the boundaries to unity amplitude at its center [4].

We first note that the rectangle windowed transform exhibits spectral leakage from the strong signal region that spills into the neighboring spectral region and nearly covers the low-level spectral mass to its left [10].
Figure 3.12. Constellation diagram before and after matched filter for low SNR.

This spectral leakage does not appear in the spectrum formed with the Kaiser-Bessel window as shown in Figure 3.16. The spectral leakage is observed as a frequency and signal dependent bias [4].

The lesson here is that windowing is required if we are to detect low level signals in the presence of nearby high level signals.

The response to the inconsistency of the DFT spectral estimate is to select a transform length required to obtain the desired spectral resolution accepting the variance associated with transform length and then reduce the variance by forming an ensemble average over many realizations [4].

The Spectra is ensemble averaged over a number of iterations so as to reduce the variance and thereby obtaining a reliable estimate is depicted in Figure 3.17.

The output spectra is fed to an integrator which specifies the observation time interval ‘T’ and compared with the threshold to decide whether a signal is present or not. There are
Figure 3.13. Frequency response output of matched filter.

Figure 3.14. Block diagram for energy detector.
several drawbacks of energy detectors that might diminish their simplicity in implementation [6]. First, a threshold used for primary user detection is highly susceptible to unknown or changing noise levels. Even if the threshold would be set adaptively, presence of any in-band interference would confuse the energy detector. Furthermore, in frequency selective fading it is not clear how to set the threshold with respect to channel notches. Second, energy detector does not differentiate between modulated signals, noise and interference. Since, it cannot recognize the interference, it cannot benefit from adaptive signal processing for canceling the interferer. Since, it cannot recognize the interference, it cannot benefit from adaptive signal processing for canceling the interferer. Spectrum policy for using the band is constrained only to primary users, so a cognitive user should treat noise and other secondary users differently. Lastly, an energy detector does not work for spread spectrum signals: direct sequence and frequency hopping signals, for which more sophisticated signal processing algorithms, need to be devised. In general, we could increase detector robustness by looking into a primary signal footprint such as modulation type, data rate, or other signal feature.
Figure 3.16. Frequency response of the Kaiser window with main lobe width $\alpha = 3\pi$ (inside, impulse response of the Kaiser window).

Figure 3.17. Spectrum of single windowed FFT and averaged windowed FFTs.
CHAPTER 4

PROPOSED IMPLEMENTATION

4.1 Cyclostationary Detection and Its Proposed Variations

Modern digital communication signals do not insert carriers or pilot signals that the receiver could access to aid in the demodulation process. They are not included in the modulation process for reasons of power efficiency (battery life and heating load). These systems rely on the ability of the receiver to reconstruct carrier and symbol timing clocks from secondary attributes of the modulated signal. These attributes are related to the excess bandwidth of the signal and statistics such as the absolute value of the mean, variance and autocorrelation of the underlying modulated waveform. Observables related to information is used with a pair of phase locked loops (PLLs) to control the frequency and phase of their associated local oscillators and thus form estimates of the desired carrier and timing clock.

4.2 Spectral Line Generation

We observed that the received signal does not contain spectral components related to the carrier or to the symbol clock. The PLL requires the equivalent of a spectral line to perform the synchronization process [11]. A spectral line is generated implicitly or explicitly by subjecting the received signal to a non-linearity such as a detector or decision quantizer. One common method of generating a spectral line for timing recovery is to square the received signal. For complex signals the squaring operation is implemented as a conjugate product. The squaring operation generates a spectral line at the symbol rate proportional to the excess bandwidth of the input spectrum at the band edge. This line is due to the cyclostationarity of the modulation process [11]. We note that when the spectrum exhibits excess bandwidth, the mean of the squared waveform is periodic and it is this periodicity which is responsible for the spectral line. A typical example showing generation of carrier spectral lines is shown below.
Consider a zero mean stationary random process \( x(t) = a(t) \cos(2\pi f_0 t) \). Upon performing the squaring operation, we get:

\[
y(t) = x(t)^2 = a(t)^2 \cos^2(2\pi f_0 t)
\]

Using Trigonometric identities, we get:

\[
y(t) = \frac{1}{2} [b(t) + b(t) \cos(4\pi f_0 t)] \text{ where } b(t) = a(t)^2
\]

We can say that \( b(t) \) is positive and with this it has a DC component or spectral line that would appear together with the spectrum at \( f = 0 \) on the PSD. This way, we can in turn assure that the Power Spectral Density (PSD) of \( y(t) \) contains scaled copies of \( b(t) \) PSD (including the spectral line) at \( \pm 2f_0 \) and of.

\[
S_y(f) = \frac{1}{4} \left[ K\delta(f) + S_b(f) + K\delta(f \pm 2f_0) + \frac{1}{4} S_b(f \pm 2f_0) \right]
\]

Figure 4.1 clarifies it.

![Figure 4.1. Depiction of spectral lines.](image)

Now, in order to eliminate the DC at zero and to reduce modulation noise contained in the detected spectra, we proposed variations to the cyclostationary detection.

First Variation as illustrated in Figure 4.2 (bottom), we multiply the original sequence \( x(n) \) with its time delayed conjugate \( x(n-4) \). We notice that the DC spectral line is completely eliminated with only the two timing spectral lines at the band edges. However there is significant modulation noise which needs to be reduced.
In the second variation we multiplied the original sequence $x(n)$ with its filtered derivative conjugate. As noticed from Figure 4.2, the DC level at zero and the modulation noise is significantly reduced due to orthogonality of the derivative product as depicted in Figure 4.3.

Third variation, we obtain the Band Edge Product using Band-Edge filtering. The spectra of the band-edge filters exhibit even-symmetry about the band-edge center frequency [11]. The received signal has been shaped at the transmitter by a square-root Nyquist Filter. The receiver will process the received signal by a matched filter with the same spectral response. Now let us assume we have access to versions of the matched filter translated by plus and minus the symbol rate. As shown in Figure 4.4, all three filters process the received signal, but we are only concerned here with the output of the translated filters.

Figure 4.5 also indicates the spectra of the filter outputs. The overlapped spectral regions of the input spectrum (which is the same as that of the matched filter) and the
translated matched filters form the desired even symmetric band edge spectra [11]. The output of these offset filters can then be combined to form the even and the odd symmetric (with respect to zero frequency) band edge filters. As seen from the Figure 4.5, band edge filtered product reduces both the DC at zero and the modulation Noise.

4.3 CHANNELIZERS

In a wireless communication receiver, channelization is the process of extracting individual narrowband radio channels from the digitized wideband input signal and providing these channels at baseband for further processing [12]. Discrete Fourier transform filter banks (DFTFBs) are widely employed for the channelization purpose. This is because they efficiently utilize the polyphase decomposition of the prototype filter so that the prototype filter can be operated at a significantly reduced sampling rate. Polyphase Channelizers having spectral shifter are used to move the filter position in SDR receiver for bandpass filtering. It will not only split the data in multiple paths to reduce the per arm data rate but the
filter also operates at lower rate than the input sample frequency. In standard channelizer designs the bandwidth of the prototype is specified in accord with the end use of the channelizer outputs as shown in Figure 4.6.

For instance, when the channelizer is used as a spectral analyzer, the channels may be designed to have specified pass band attenuation such as –3 dB, or –1 dB or –0.1 dB at their crossover frequency and have specified stop band attenuation at their adjacent center frequency [12]. Overlap of adjacent channel responses permits a narrow band input signal to straddle one or more output channels, which is a common occurrence in the spectral analysis of signals with arbitrary bandwidth and center frequencies. On the other hand, when a channelizer is used to separate adjacent communication channels which are characterized by known center frequencies and known controlled, no overlapping bandwidths, the channelizer must preserve separation of the channel outputs. Inadequate adjacent channel separation
Figure 4.5. Third variation: Cyclostationary BE product.

Figure 4.6. Polyphase channelizer with folded window.
results in adjacent channel interference [8]. Typical spectral responses for channel bandwidths corresponding to the two scenarios just described are shown in Figure 4.7.

Figure 4.7. Multiple instantiation of the prototype filter capturing different bands (channels).

The polyphase filter channelizer uses the input M-to-1 resampling to alias the spectral terms residing at multiples of the output sample rate to base band. This means that for the standard polyphase channelizer, the output sample rate is the same as the channel spacing. For the case of the spectral analyzer application operating at this sample rate permits aliasing of the band edges into the down sampled pass band [12]. When operated in this mode, the system is called a maximally decimated filter bank. For the case of the communication channelizer, operating at this rate satisfies the Nyquist criterion, permitting the separation of the channels with an output rate that avoids band edge aliasing. An example of a spectrum that would require this mode of operation is the Quadrature Amplitude Modulation (QAM) channels of a digital cable system as shown in Figure 4.8.
4.4 IMPLEMENTATION OF 40 CHANNEL CHANNELIZER

Next, we implemented a 40 channel receiver demodulating 30 channels of different amplitude levels and bandwidths, of nominal symbol rate 20 MHz, separated by 28 MHz centers (1.4 times symbol rate) input sample rate is 40*28 = 1120 MHz Receiver performs a 40 point transform on the output of a 40-stage polyphase filter. The polyphase filter operates at input rate but outputs at 2 samples/symbol or 40 MHz.

The resampling rate is 1120/40 = 28-to-1, thus output from 40-channels are computed once for every 28 input samples. Channelizer is not matched filter, but a prototype filter that is 10% wider than the two-sided bandwidth of input signal to accommodate frequency uncertainty of separate channel centers.

A composite Spectrum of different signals is shown in Figure 4.9.

This Composite time signal is made to pass through a channel affected by AWGN as shown in Figure 4.10.
Next 40 channel channelizer is implemented demodulating 30 individual narrowband channels for low SNR is shown in Figure 4.11.

Even though the spectra in Figure 4.12 exhibit high variance, individual channels can be easily detected because of high SNR of the signals.
Figure 4.11. Composite spectra with/without noise (low SNR condition).

Figure 4.12. Spectra of individual channels without averaging (high SNR, easily detectable).
For the low SNR condition as shown in Figure 4.13, it is difficult to identify the presence of the signal in the individual bands after demodulation. Further we ensemble average the Spectra for both the High SNR and Low SNR condition.

![Figure 4.13. Spectra of individual channels without averaging (low SNR, hardly detectable).](image)

The spectra shown in Figure 4.14 (High SNR condition) and Figure 4.15 (Low SNR condition) shows the effect of ensemble averaging to reduce variance thereby improving resolution of the spectral estimate. However, a trade-off exists as to increasing the number of averaging iterations reduces the processing speed of the cognitive radio.

### 4.5 Effect of Band-Edge Filtering

With the implementation Band-Edge Processors, we are able to generate spectral lines with significantly reduced data pattern induced jitter. The cross product of these two optimally shaped and phase shifted band edge filters leads to a remarkable output containing a spectral line at the symbol rate and exhibits no pattern dependent jitter.

The spectral lines in the narrowband channels indicate the presence of signals as shown in the Figures 4.16 and 4.17.
Figure 4.14. Spectra of the individual channels for high SNR with averaging (very easily detectable).

Figure 4.15. Spectra of the individual channels for low SNR with averaging (detectable).
Figure 4.16. Band edged spectra of the channels after averaging (for good SNR condition).

Figure 4.17. Band edged spectra of the channels after averaging (for low SNR condition).
4.6 CONCLUSION

We have discussed a number of spectrum sensing techniques like the Matched Filter Technique, Energy Detection Technique, Cyclostationary Technique and proposed variations to the same by realizing an efficient signal processing scheme which employs a combination of channelization, generating spectral timing lines using band-edge processors and ensemble averaging to detect multiple active individual narrow-band channels based on the sensing output of the Discrete Fourier transform Banks. The detection shows remarkable performance in terms of complexity, variance reduction and improved resolution of spectral estimates. In terms of performance, the Energy detector is the easiest to implement, however its threshold is highly susceptible to inband and outband noise. Even the matched filter is a comparable technique, but the matched filter can detect signals of particular symbol rate and not a wide array of different band-limited signals. In terms of performance under Noise, Cyclostationary Technique is an optimal technique but has higher sensing times as compared to other techniques.
BIBLIOGRAPHY


