Status of Thesis

Title of thesis	**Cyclostationary Features of PAL TV and Wireless Microphone for Cognitive Radio Applications**

I ALFATEH MOHAMMED ALHASSAN MOSSA hereby allow my thesis to be placed at the Information Resource Center (IRC) of Universiti Teknologi PETRONAS (UTP) with the following conditions:

1. The thesis becomes the property of UTP.
2. The IRC of UTP may make copies of the thesis for academic purposes only.
3. This thesis is classified as

☐ Confidential

☑ Non-confidential

If this thesis is confidential, please state the reason:

____
____
____

The contents of the thesis will remain confidential for ___________ years.

Remarks on disclosure:

____
____
____

Endorsed by

__________________	_____________________
Signature of Author	Signature of Supervisor
Permanent Address:	
House #1099, Althora 24	
Omdurman, Khartoum State	
Sudan	*Assoc. Prof. Dr. Varun Jeoti*
Date: __________________	Date: ___________________

UNIVERSITI TEKNOLOGI PETRONAS

"CYCLOSTATIONARY FEATURES OF PAL TV AND WIRELESS MICROPHONE FOR COGNITIVE RADIO APPLICATIONS"

by

ALFATEH MOHAMMED ALHASSAN MOSSA

The undersigned certify that they have read, and recommend to the Postgraduate Studies Programme for acceptance this thesis for the fulfillment of the requirements for the degree stated.

Signature: ____

Main Supervisor: *Assoc. Prof. Dr. Varun Jeoti*

Signature: ____

Co-Supervisor: ____

Signature: ____

Head of Department: *Dr. Nor Hisham Hamid*

Date: ____

"CYCLOSTATIONARY FEATURES OF PAL TV AND WIRELESS MICROPHONE FOR COGNITIVE RADIO APPLICATIONS"

by

ALFATEH MOHAMMED ALHASSAN MOSSA

A Thesis

Submitted to the Postgraduate Studies Programme

as a Requirement for the Degree of

MASTER OF SCIENCE

ELECTRICAL AND ELECTRONICS ENGINEERING

UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SERI ISKANDAR,

PERAK

MAY 2010

DECLARATION OF THESIS

Title of thesis **Cyclostationary Features of PAL TV and Wireless Microphone for Cognitive Radio Applications**

I ALFATEH MOHAMMED ALHASSAN MOSSA

hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

Witnessed by

____
Signature of Author

Permanent address:
House #1099, Althora 24
Omdurman, Khartoum State
Sudan

Date: ______________________

____
Signature of Supervisor

Name of Supervisor:
Assoc. Prof. Dr. Varun Jeoti

Date: ___________________

ACKNOWLEDGEMENT

First and foremost, I would like to thank God the Almighty for guiding me along in completing this work. I am also indebted to my family for their untiring support and I could not have accomplished this work without their endless encouragement.

I would like to express my sincere appreciation to my supervisor Dr. Varun Jeoti for his continuous guidance and support during my M.Sc. program. I also thank faculty, staff and fellow students of the Department of Electrical and Electronics Engineering who have helped me.

ABSTRACT

Frequency spectrum being a scarce resource in communication system design, spectrum sharing seems to be the solution to an optimal utilization of frequency spectrum. The traditional fixed frequency allocation is not suitable for futuristic networks that demand more and more spectrum for new wireless services. Cognitive radio is a new emerging technology based on spectrum sharing concept.

Spectrum sensing is a vital task in this emerging technology by which it is able to scan the frequency spectrum to identify the unused spectrum bands and utilize them. In this thesis, we discuss spectrum sensing in the context of IEEE 802.22 Wireless Regional Area Network (WRAN). In order to do so, we develop the co-existence scenario with three cases according to geographical positions of primary services and secondary service. In WRAN application, the SUs utilize the unused channel in TV spectrum, which means that the primary users are TV service and other FCC part 74 low power licensed devices. We focus on special case of Analog TV-PAL service and wireless microphone service as part 74 devices. Before discussing the spectrum sensing technique, we propose architecture for sensing receiver. The concept of noise uncertainty is also introduced in this context. The cyclostationarity theory is introduced and we explain the motivation behind using the theory for spectrum sensing and the reason that makes the cyclostationary features detector a powerful detection technique in cognitive radio. We obtain the cyclostationary features of these primary signals using spectral correlation function. Based on these features, we develop two algorithms for spectrum sensing and their performances are evaluated in comparison with energy detector which is considered as the standard simple detector.

Given that the cyclostationary features are unique for a particular signal; these features can be used for signals classification. In our case, we use those features to decide if the licensed channel is used by TV service or wireless microphone service. This provides additional information for spectrum management and power control.

Implementation issue is very important in cognitive radio generally and spectrum sensing specially, hence we discuss the implementation of cyclostationary features detector and compare its complexity with that of energy detector.

ABSTRAK

Spektrum frekuensi adalah sumber yang sukar didapati dalam rekabentuk sistem komunikasi, maka perkongsian spectrum dilihat sebagai penyelesaian terhadap penggunaan optima spektrum frekuensi. Pengagihan frekuensi tetap secara tradisi tidak sesuai untuk jaringan futuristik yang menuntut semakin banyak spektrum untuk perkhidmatan wayarles. Radio kognitif adalah satu teknologi baru yang sedang muncul yang berasaskan konsep perkongsian spectrum.

Pengesanan spektrum adalah satu tugas amat penting dalam teknologi yang sedang muncul ini di mana ia berupaya mengimbas spektrum frekuensi untuk mengenalpasti jalur spektrum yang tidak digunakan dan menggunakannya. Di dalam tesis ini, kami membincangkan pengesanan spektrum dalam konteks IEEE 802.22 Wireless Regional Area Network (WRAN). Untuk berbuat demikikan, kami membangunkan senario kewujudan bersama menggunakan tiga kes mengikut lokasi geografi perkhidmatan primer dan perkhidmatan sekunder. Dalam aplikasi WRAN, SU menggunakan saluran yang tidak dipakai dalam spektrum TV, bermakna pengguna utama adalah perkhidmatan TV dan FCC lain bahagian 74 peralatan berkuasa rendah yang berlesen. Kami memfokus kepada kes istimewa perkhidmatan TV-PAL Analog dan perkhidmatan mikrofon wayarles sebagai sebahagian dari peralatan 74. Sebelum membincangkan teknik pengesanan spectrum, kami mencadangkan seni bina untuk alat penerima pengesanan. Konsep ketidakpastian bunyi juga diperkenalkan dalam konteks ini. Teori cyclostationary diperkenalkan dan kami menerangkan motivasi di sebalik penggunaan teori untuk pengesanan spectrum dan sebab yang menjadikan pengesan berciri cyclostationary sebagai teknik pengesanan yang sangat berkesan dalam radio kognitif. Kami memperolehi ciri-ciri cyclostationary isyarat primer ini menggunakan fungsi korelasi spektra. Berdasarkan ciri-ciri tersebut, kami membangunkan dua algorisma untuk pengesanan spektrum dan prestasi mereka dinilai berbanding dengan pengesan tenaga yang dianggap sebagai pengesan ringkas piawai.

Memandangkan ciri-ciri cyclostationary adalah unik bagi suatu isyarat tertentu, ciri-ciri ini boleh digunakan untuk pengkelasan isyarat. Bagi kes kami, kami menggunakan ciri-ciri tersebut untuk menentukan samada saluran berlesen itu digunakan oleh perkhidmatan TV atau perkhidmatan mikrofon wayarles. Ini memberikan maklumat tambahan untuk pengurusan spektrum dan pengawalan kuasa.

Isu implementasi adalah sangat penting dalam radio kognitif amnya dan pengesanan spectrum khususnya, maka kami membincangkan pelaksanaan pengesan berciri cyclostationary dan membandingkan kerumitannya dengan pengesan tenaga.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND SYMBOLS

ATSC	Advanced Television Systems Committee
BS	Base station
CAF	Cyclic Autocorrelation Function
CDF	Cumulative Distribution Function
CPE	Customer Premise Equipment
CR	Cognitive Radio
CSD	Cyclic Spectral Density
DSA	Dynamic Spectrum Access
DVB-T	Digital Video Broadcasting - Terrestrial
FAM	FFT accumulation method
FCC	Federal Communications Commission
FFT	Fast Fourier Transform
FM	Frequency Modulation
IEEE	Institute of Electrical and Electronics Engineering
MAC	Media Access Control
NTSC	National Television System Committee
OFDMA	Orthogonal Frequency Division Multiple Access
PAL	Phase Alternating Line
PDU	Protocol Data Unit
PHY	Physical Layer
PSD	Power spectral density
PU	Primary User
QoS	Quality of Service
RF	Radio Frequency
RFE	Radio Front-End
SCF	Spectral Correlation Function
SCH	Super Frame Control Header
SDR	Software-Defined Radio
SECAM	Sequential Color with Memory

SNR	Signal to Noise Ratio
STFT	Short Time Fourier Transform
SU	Secondary User
UHF	Ultra High Frequency
UWB	Ultra Wideband
VHF	Very High Frequency
VSB	Vestigial Side-Band
WG	Working group
AWGN	Additive White Gaussian Noise
WiMic	Wireless Microphone
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WRAN	Wireless Regional Area Network
N	Noise Power
N_0	Thermal Noise Power Spectral Density
N_s	Number of Samples During Sensing Time
P_c	Probability of correct classification
P_d	Probability of detection
P_{fa}	Probability of false alarm
P_{md}	Probability of missed detection
$Q(x)$	Complementary Cumulative Distribution Function
$R_x^{\alpha}(\tau)$	Cyclic Autocorrelation Function
$S_x^{\alpha}(f)$	Spectral Correlation Function
TS	Test statistics
t_s	Sensing Time
σ_w^2	White Gaussian Noise Variance
σ_x^2	Primary Signal Variance
λ	Decision Threshold

CHAPTER 1

INTRODUCTION

1.1 Motivation

The key issue in wireless systems is the availability of the frequency spectra. As the communications services quickly grow, there will be a demand for more frequency spectra. Under the fixed allocation of frequency, specific spectrum bands are assigned to a certain wireless services and with the current increasing demand for spectra we will face spectrum scarcity. Frequency spectrum is a limited and valuable resource, hence there is serious research work underway considering this issue.

To better evaluate this situation, there are many measurements of spectrum utilization at different locations. One of those frequency occupancy is shown in Figure 1-1, which is part of the National Radio Network Research Testbed (NRNRT) project [1]. With current frequency allocation, there is little bandwidth available to be used by future wireless services. But, this measurement shows that most of the assigned frequency bands are not fully utilized at every location and time.

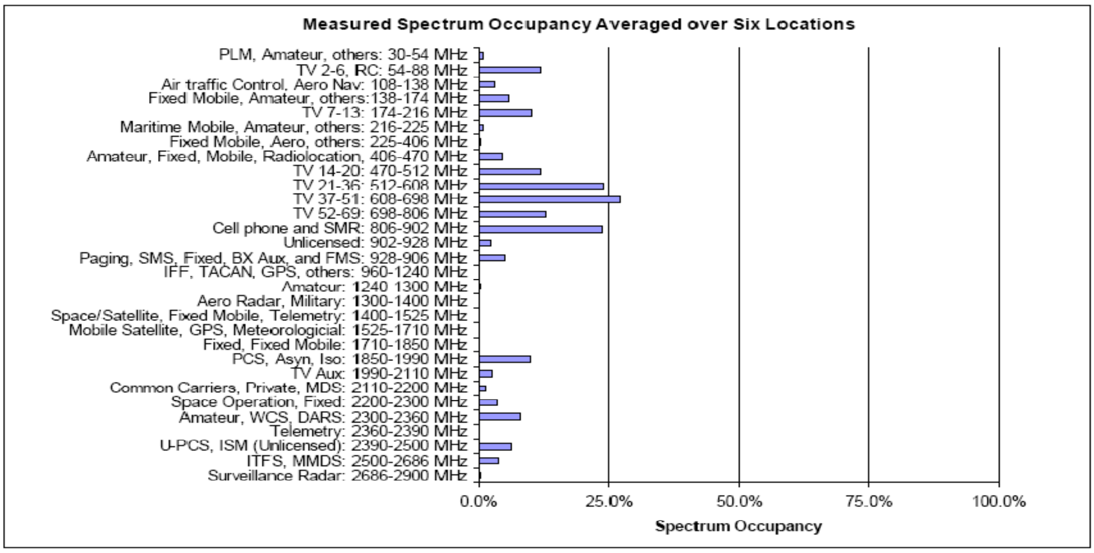

Figure 1-1: Spectrum occupancy in each band averaged over various locations [1]

Hence, the fundamental problem is not the scarcity of the frequency bands but how they are utilized. To improve spectrum utilization the current spectrum allocation can not be easily changed because this affects the access right of the licensed users of the spectrum. Most of the research work on this issue considers opportunistic spectrum sharing between wireless services [2]-[4]. In this regime, we have the primary user (PU) the licensee of frequency bands and the secondary user (SU) the unlicensed user which allowed sharing the spectrum with the PU without causing harmful interference to this PU. There are two approaches of opportunistic spectrum sharing, the first approach is Ultra Wideband (UWB) and the second approach is cognitive radio (CR). In the first approach which was approved by the Federal Communication Committee (FCC) in 2002 [5], the SU transmits in same PU frequency band using limited transmission power spread over wide frequency band as shown in Figure 1-2. This approach is suitable for Wireless Personal Area Network (WPAN).

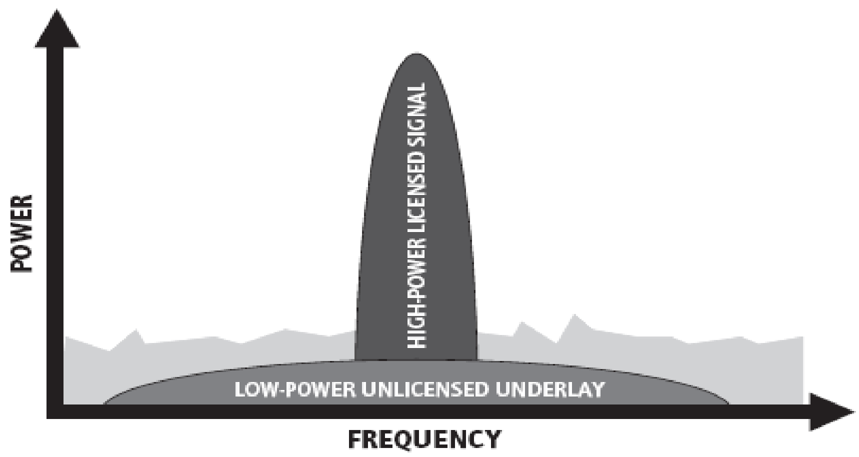

Figure 1-2: UWB spectrum sharing approach

The second approach was first introduced by Mitola [6] and was approved later by FCC in 2004 [6]-[8]. This approach addresses the problem of limited transmission power in UWB by using the frequency bands licensed to PU, but are not being utilized by that user at a particular time and specific geographic area [9]. As illustrated in Figure 1-3 [10], these frequency bands are called white spaces or spectrum holes and represent the available opportunities for SUs to utilize them with higher transmission power. Using spectrum holes without restricted power levels, makes CR a suitable technology for wide coverage area applications.

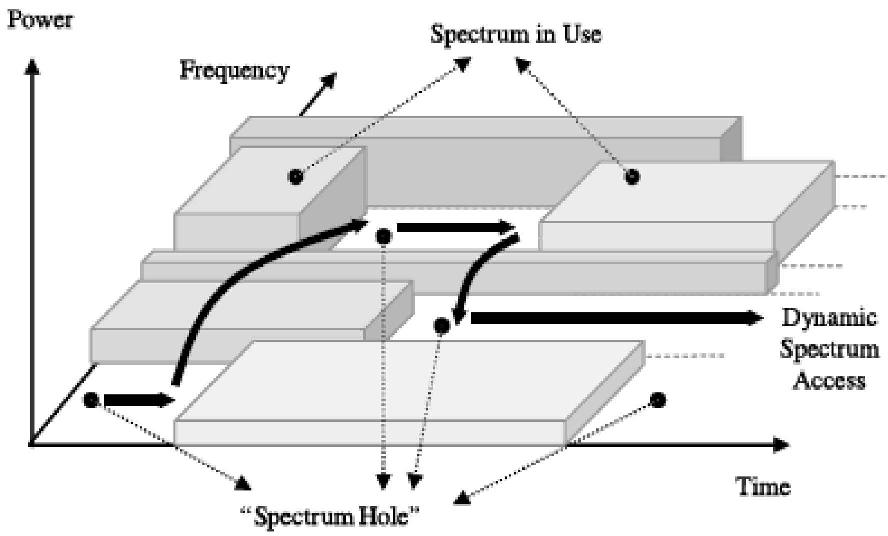

Figure 1-3: Cognitive radio spectrum sharing approach [9]

CR is currently a very active research area and attracts serious research works around the world [8]-[11], especially after IEEE 802.22 working group for Wireless Regional Area Network (WRAN) was established which is the first wireless standard based on CR. In CR, detection of spectrum holes (spectrum sensing) and protection of PUs are critical tasks. This thesis and research have been motivated by:

- The importance of improving spectrum utilization and the promising CR which requires better spectrum sensing using reliable sensing techniques.
- According to the authors' best knowledge, there is no work done considering analog TV-PAL as a primary service in WRAN 802.22 context and using cyclostationary features detector as a spectrum sensing technique.

Currently, TV-PAL system is used in over 120 countries and territories, which is strong motivation to be considered as the main primary service in WRAN CR.

1.2 Cognitive Radio

CR is a paradigm for wireless communication in which either network or wireless node itself changes particular transmission or reception parameters to execute its tasks efficiently. This parameter alteration is based on observations of several factors from external and internal cognitive radio environment, such as radio frequency spectrum, user behavior, and network state.

CR enables flexible, efficient and reliable spectrum use. It makes it possible for radio devices to sense the surrounding environment and effectively adapt their parameters according to current channel conditions and quality of service (QoS) specifications. It has the potential to utilize the unused spectrum in an intelligent way while not interfering with PUs (licensed users) in their frequency bands [6].

CR concept was first defined by Joseph Mitola III [6], which was based on software-defined radio (SDR). The benefit of the SDR technology is to undertake all required signal processing by using software. Hence, there would be no need for hardware changes or upgrades when changing the transmission bands or forms. Figure 1-4 shows the difference between traditional radio, SDR and CR. The focus has lately turned from SDR to CR systems because it has not only the flexibility of SDR but also the intelligence. This intelligence makes CR systems aware of its environment, and capable of learning from its behavior, observations and feedback, and also performing functions that best serve its user [12]. It is important to notice that CR does not operate in a fixed band; it rather searches and finds an appropriate band to operate.

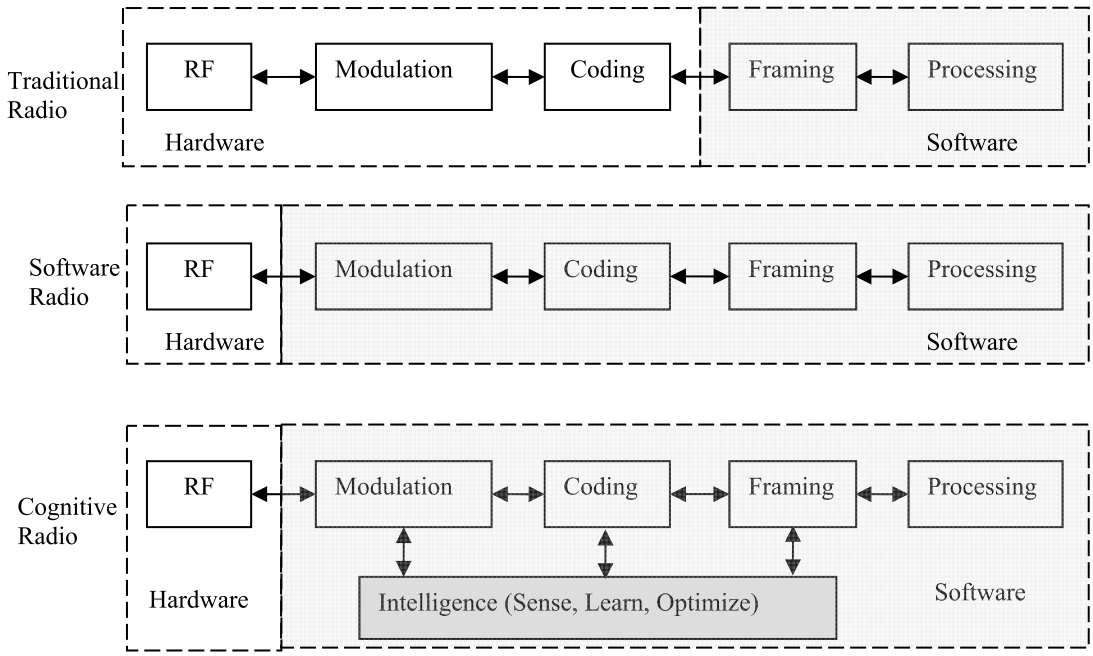

Figure 1-4: Radio technologies [6]

In order that the CR can utilize efficiently the appropriate bands of available white spaces, it has these main functions [9]:

- Spectrum sensing: Detecting unused spectrum (white spaces) using a reliable technique that guarantees no harmful interference is caused to PUs.
- Spectrum management: Finding the best white spaces to meet user communication requirements. It includes these two functions:
    - Spectrum analysis: Each spectrum hole should be characterized hence the quality of a particular spectrum band can be determined. Channel capacity is the most important factor of spectrum characterization.
    - Spectrum decision: It is based on QoS requirement of SU and after the spectrum holes are characterized, an appropriate hole should be chosen for SU transmission.
- Spectrum mobility: This function maintains seamless communication requirements when better frequency spectrum is found.
- Spectrum sharing: To allow spectrum scheduling method among coexisting SUs. This function addresses the problem of spectrum allocation in CR.

As shown in Figure 1-5 [9], spectrum sensing is a physical layer issue and there is cooperation between spectrum sensing and spectrum sharing (link layer). This cooperation is better addressed as cross-layer approach to enhance spectrum efficiency. Also, there is cooperation between each of spectrum management and spectrum mobility functions and all layers which is necessary in CR to support flexibility and adaptability. The interaction with the environment is the first task to obtain the required information that can be used to adapt the operating parameters of CR user to best use of available resources. This interaction can be represented as simplified cognitive cycle [12] as in Figure 1-6. It is obvious that spectrum sensing is the first cognitive task that precedes all other tasks of spectrum management. First, during spectrum sensing SU is able to search the available spectrum holes and then allocate them for further use. Second, those spectrum holes are characterized during frequency spectrum analysis task of cognitive cycle and this task results in estimation of the channel capacity of these spectrum holes. Finally, decision will be made about which spectrum hole can used for current QoS of SU.

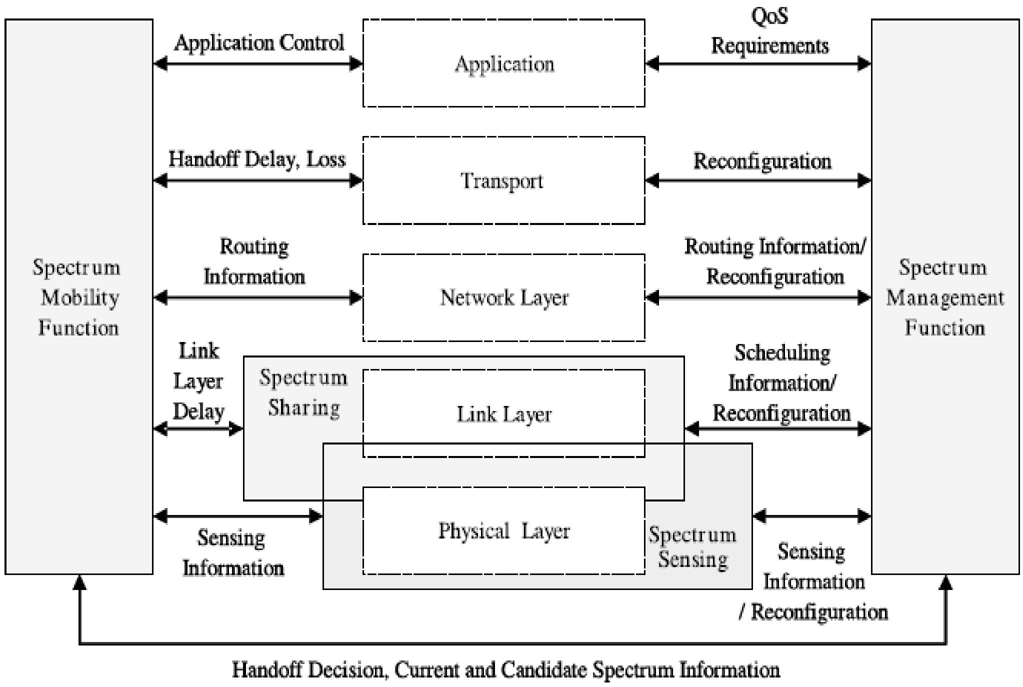

Figure 1-5: CR functionalities and communication layers [9]

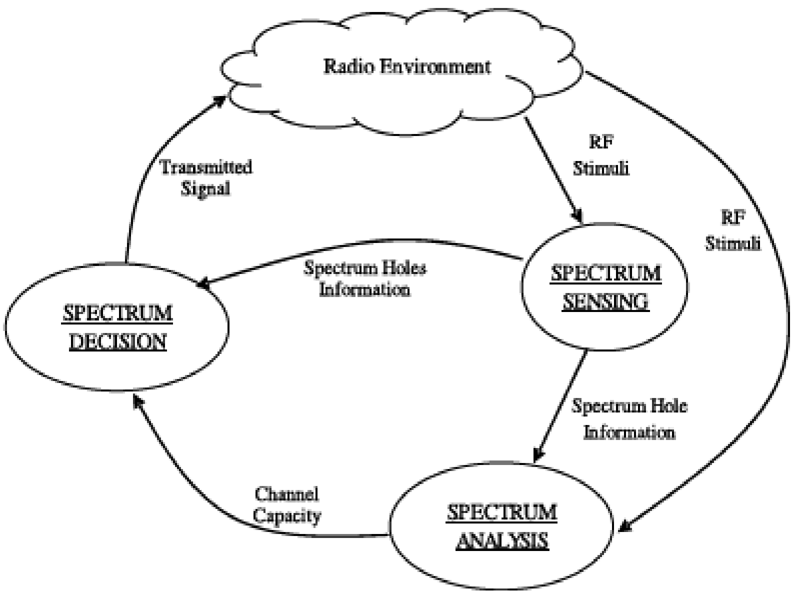

Figure 1-6: Cognitive cycle [12]

1.3 Problem Statement

This thesis focuses on the problem of spectrum sensing in the context of WRAN CR when TV-PAL and wireless microphone are the PUs. Spectrum sensing problem can be formulated as binary detection hypotheses and the reliability of spectrum sensing can be measured by probability of detection (P_d) and probability of false alarm (P_{fa}). There are two serious problems which can affect the reliability of any spectrum sensing technique. The first one is "hidden terminal problem". In this case, there is no line-of-sight between PU transmitter and SU receiver (sensing receiver), hence the primary signal is shadowed and very weak at SU receiver and at the same time, SU may have a line-of sight path to PU receiver. Consequently, the erroneous sensing decision may result that the primary channel is vacant and is available for transmission, which will then cause harmful interference to PU receiver. This problem requires high spectrum sensing sensitivity to detect weak PU signal. The second problem is the problem of "sensing time". When the PU uses the frequency band only over shorts periods of time, it requires the SUs to quickly and frequently sense the frequency bands which are under their use. This will keep SU continuously monitoring the spectrum holes if PUs have reappeared. Hence, the sensing time available can be too short for any useful application. Sensitivity and sensing time are the critical issues in spectrum sensing problem and also for spectrum sensing evaluation.

1.4 Objectives

This thesis considers analog TV-PAL and wireless microphone services as the primary services in WRAN IEEE 802.22. The main objectives of this thesis can be summarized as follows:

- Within the context of WRAN, to study the co-existence scenario of SU and analog TV-PAL and wireless microphone as PUs.

- To propose radio front-end (RFE) architecture for the sensing receiver and the corresponding noise floor estimation. This also includes modeling of noise uncertainty.
- To obtain the cyclostationary features of analog TV-PAL and wireless microphone.
- To develop spectrum sensing algorithms for TV-PAL and wireless microphone based on their cyclostationary features.
- To develop signal classification algorithm to differentiate between TV-PAL and wireless microphone signals based on their cyclostationary features.
- To evaluate the performance of these algorithms compared with that of energy detector as the default detector.

1.5 Research Methodology

According to the outlined problem statement and research objectives, a clear view of the spectrum sensing problem is not available in WRAN 802.22 context without calculating the power levels of PUs at SU receiver. Accordingly, the co-existence scenario is first studied and analyzed. This study provides the knowledge of the weakest PU signal the ideal detector can detect. The evaluation of the spectrum sensing algorithm is mainly based on its sensitivity i.e. the minimum signal-to noise ratio (SNR) at which the spectrum sensing is able to achieve the required P_d. Hence, the noise floor at RFE should be estimated and combined with the calculated signal powers to obtain the received SNRs at the input of the spectrum sensing algorithm. MATLAB® is used to simulate the primary signals and obtain their cyclostationary features using spectral correlation function. Noise is assumed to be Additive White Gaussian Noise (AWGN) and its spectral correlation function is also obtained. Theoretically, AWGN has no cyclostationary features and this is also seen using simulation. In order to evaluate the proposed algorithms, four factors are considered; SNR, P_d, P_{fa} and sensing time. Beside these factors, effects of noise uncertainty and wireless channel are also considered. The performance is evaluated in comparison with that of energy detector. The steps for performance evaluation using these factors are as follows:

- To use WRAN 802.22 standard to obtain the required P_d, P_{fa}.
- To use the appropriate sensing time and SNRs range to compare between energy detector and cyclostationary features detector.
- To determine the threshold for fixed P_{fa} for the sensing algorithm by using cumulative distribution function (CDF) of test statistics of AWGN.
- To model noise uncertainty using robust statistic model.
- To plot P_d against SNR hence the sensitivity of the proposed algorithms and energy detector can be evaluated for specific value of sensing time and noise uncertainty. In addition to Additive White Gaussian Noise (AWGN) channel, fading channel is also considered in the evaluation.
- In addition to the mentioned factors, probability of classification (P_c) is used to evaluate the performance of the proposed classification approach by plotting P_c against SNR.

Even though the hardware implementation is considered beyond the scope of this thesis, the complexity of the proposed cyclostationary features-based spectrum sensing technique is studied in comparison with that of the energy detector.

1.6 Contribution

The contributions of this thesis in current CR spectrum sensing research works can be pointed as follows:

- Proposed the system model in context of IEEE 802.22 WRAN standard.
- Studied the co-existence scenario between WRAN, TV-PAL and wireless microphone systems.

- Obtained the unique cyclostationary features of TV-PAL and wireless microphone signals.
- Proposed spectrum sensing algorithms based on cyclostationary features of TV-PAL and wireless microphone.
- Classified the signals of TV-PAL and wireless microphone using their cyclostationary features
- Evaluated the performance of the proposed algorithms in terms of sensitivity and classification probability.

1.7 Thesis Organization

The contents of the thesis are structured into six chapters. This chapter explains the motivation for the thesis and the importance of spectrum sensing in CR technology. The problem and the objectives are stated. Research methodology to achieve the thesis objective is also discussed. Finally, the contribution of this thesis is pointed.

Chapter 2 gives the background and literature review. It describes the architecture of IEEE WRAN 802.22 CR standard and the important features of physical and medium access layers. Sensing receiver architectures for three spectrum utilization regimes are also introduced. Then, spectrum sensing literature review in context of TV-PAL and wireless microphone signals are discussed.

In Chapter 3, co-existence scenario of WRAN 802.22, TV-PAL and wireless microphone is studied. Default system parameters are used to find the radius of co-existence area of SU. Then, the signal power levels of primary signals are calculated at SUs receivers. After that, sensing receiver architecture is proposed and noise floor calculation and noise uncertainty model are explained. Spectrum sensing model and conventional detectors which include energy detector and matched filter are also described. Then, cyclostationarity theory is introduced and used to obtain cyclostationary features of TV-PAL and wireless microphone signals and to develop a spectrum sensing model based on it. The final part of this chapter discusses the implementation issue and computational complexity of cyclostationary features detector.

In chapter 4, spectrum sensing and classification algorithms for TV-PAL and wireless microphone are proposed based on cyclostationary features obtained in chapter 3. The exact features and coordinates used in these algorithms are based on down conversion of received PUs signals. The methodology for the assessment of these algorithms is also explained in this chapter.

Chapter 5, discusses and analyzes the performance of the proposed algorithms described in chapter 4. The evaluation is provided in comparison with those of energy detector under noise uncertainty, AWGN and fading channels.

Chapter 6, concludes the thesis and summarizes the important findings and contributions and also presents the future research related to this thesis.

CHAPTER 2

WRAN, SPECTRUM SENSING AND RELATED LITERATURE REVIEW

2.1 Introduction

This chapter reviews cognitive radio specifically its IEEE 802.22, the first CR standard. It further describes the architecture of IEEE WRAN 802.22 CR standard and the important features of physical and medium access layers. Sensing receiver architectures for three spectrum utilization regimes are also introduced. Then, an extensive review of spectrum sensing literature is presented. It is seen that the work undertaken in this thesis of accurately sensing incumbent TV-PAL and wireless microphone using their cyclostationary features has not been developed before.

2.2 Cognitive Radio and Dynamic Spectrum Sharing

Wireless technology has enabled the development of various applications resulting in an exponential growth in usage and services. To cope with this growth, more complex algorithms have been designed to increase the spectral efficiency. In parallel, advanced and complex protocols have been developed to support increasing spectral efficiency. As a result, new standards specifying the physical (PHY) and medium access control (MAC) layers have emerged. IEEE 802.22, discussed in section 2.3, is the first WRAN standard makes use of the developed concepts of CR for spectrum sharing and increased spectrum efficiency.

Advances in reconfigurable hardware (i.e., SDR) have paved the way for realizing the dream of CR which can adapt its air interface and communication protocols based on observations from operating environment. The combination of flexibility and increased protocol intelligence gives the CR the ability to optimize the performance and satisfy user requirements [14].

While its generic form includes flexibility in all communication functions, basic form of the CR requires achieving dynamic spectrumaccess (DSA) which results in a very efficient use of the spectrum. In DSA, which is the opposite of the current spectrum allocation, a SU (unlicensed) shares a frequency band with designated PUs (licensed) without causing interference or performance degradation to the PUs [10]. SU has the ability to dynamically adapt to available spectrum holes in response to changing circumstances such as interference experienced or received command. In context of CR, DSA is also called dynamic spectrum sharing.

As mentioned in section 1.2 and illustrated in Figure 1-5, to support dynamic spectrum sharing, CR has four main functions: spectrum sensing, spectrum management, spectrum mobility and spectrum sharing [10]. These are briefly described as follows:

a) Spectrum Sensing

To be able to adapt to the changing wireless environment, it is crucial to monitor it in detail. Monitoring the available spectrum bands to detect spectrum holes is called spectrum sensing. For dynamic spectrum sharing, important information is related to the spectrum use by other nodes in the network. These other users can be PUs or SUs which are not necessarily equipped with cognitive capability; hence it is necessary to recognize the presence of the different users. Section 2.6 provides background of spectrum sensing techniques.

b) Spectrum management

After spectrum sensing, the detected spectrum holes need to be characterized. Characterization seeks to differentiate between the spectrum holes on the basis of their respective frequencies, bandwidths as well as varying radio environment. This stage of spectrum management is called spectrum analysis – an act that is attributed to upper layers, while spectrum sensing is carried out in PHY layer. Many factors can be considered for the analysis of the detected spectrum holes such as respective channel capacity, link layer delay, wireless link errors and holding time [10].

The second stage of spectrum management is spectrum decision. At this stage, user requirements are used to decide which set of spectrum holes is the best for these requirements. To make the decision, several factors are determined based on user requirements such as the data rate, acceptable data error, delay and bandwidth.

c) Spectrum Mobility

Because CR seeks to use the best available spectrum holes for specific user requirements, there is a need to support transparent spectrum transition from one hole to another. This happens when better characterized spectrum holes are detected by spectrum sensing or the current spectrum hole experiences worse channel conditions. In the context of CR, this spectrum mobility is called spectrum handoff [10]. In spectrum mobility, the upper network protocols should be adaptive hence that they can change from one mode of operation to another when the operating frequency (spectrum hole) is changed.

d) Spectrum Sharing

In addition to spectrum sharing with PUs, CR also addresses spectrum sharing among SUs. Based on the available spectrum holes, SU can allocate a channel and access of this channel should be coordinated in order to prevent multiple users colliding. There are two approaches for this coordination: centralized and distributed [4]. In centralized spectrum sharing, a centralized entity controls the spectrum allocation and access procedures. In distributed spectrum sharing, each SU is responsible for the spectrum allocation and access based on local or global policies.

As this thesis focuses on spectrum sensing in WRAN CR, the next section highlights the main features of this standard and how DSA is supported in the context of PHY and MAC layers.

2.3 IEEE 802.22 WRAN Standard

The IEEE 802.22 working group (WG) was founded in November 2004, after the FCC released its Notice of Proposed Rule Making (NPRM) for TV bands in May 2004 [7]. This WG specifies an air interface (including PHY and MAC layers specifications) for WRAN to coexist with PUs in TV transmission bands [13]. This WG activity is the first world wide effort to standardize CR techniques for the opportunistic use of TV bands without causing interference to PUs (TV broadcasting and wireless microphone).

The main application for 802.22 is wireless broadband access in rural and remote area with performance comparable to those of existing fixed broadband access technologies serving urban and suburban. This new standard will help increase the availability of broadband access in those rural underserved markets [15]. WRAN shall provide services such as data, voice, audio and video traffic with appropriate QoS support. Unlike other unlicensed services such as Wireless Local Area Network (WLAN) which operates at the 5.8 GHz band in addition to the 2.4 GHz band, WRAN operates at lower frequency bands licensed for TV broadcasting and wireless microphone. The advantages of using lower frequency bands are:

- The favorable propagation conditions and less attenuation of the signal, which is suitable for providing services to large coverage area.
- The transmission unaffected by Doppler Effect.
- The lower cost of radio frequency electronics.

The IEEE 802 community wireless standards according to their coverage area are shown in Figure 2-1 [15], in which WRAN has a coverage radius up to 100 km. In the US, TV stations operate from channels 2 to 69 in the VHF and UHF portion of the radio spectrum. All of these channels are 6 MHz wide, and span from 54-72 MHz, 76-88 MHz, 174-216 MHz, and 470-806 MHz. In Malaysia, TV stations operate in the VHF Band I (47-68 MHz), the VHF Band III (174-230 MHz) and the UHF band (510-798 MHz) [16]. These channels will be opened for WRAN use on sharing non-interfering basis.

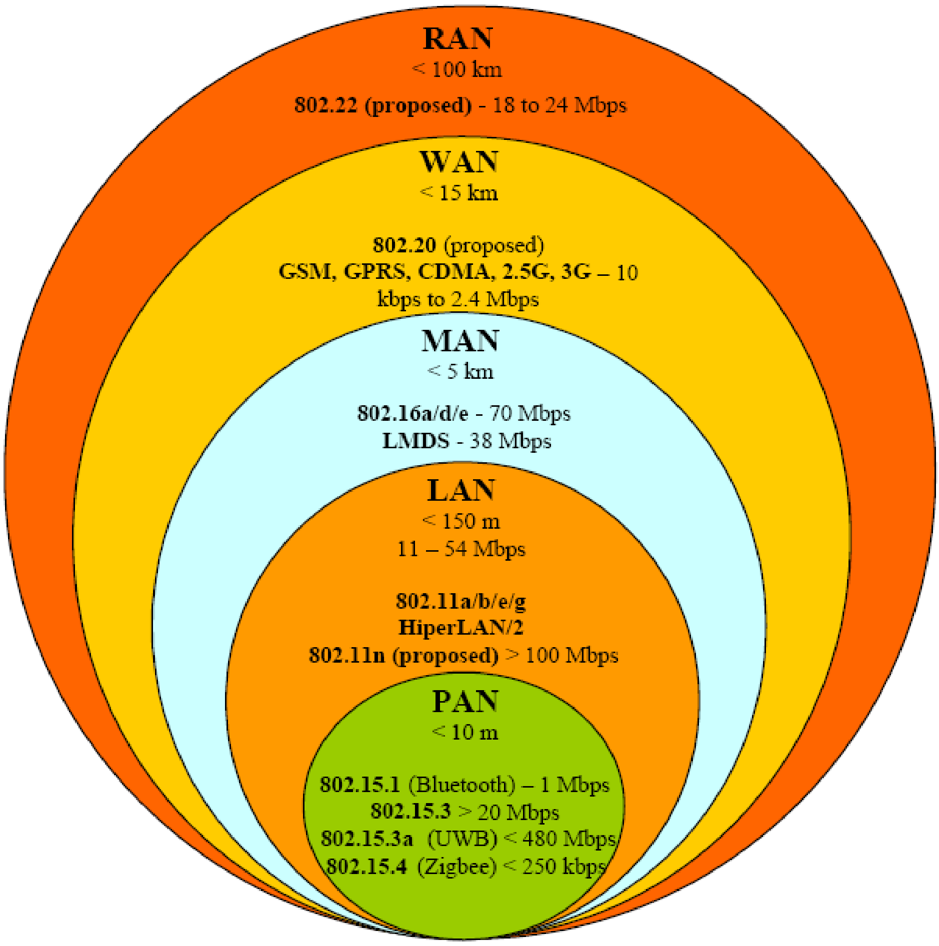

Figure 2-1: Coverage range of the different standard networks [15]

2.3.1 WRAN System Architecture

An example of a deployed WRAN is shown in Figure 2-2. WRANs operate in a fixed point-to-multi-point topology where a base station (BS) manages its own cell and all associated Consumer Premise Equipments (CPEs). The BS controls the medium access in its cell and transmits in the downstream direction to the various CPEs, which respond back to the BS in the upstream direction. In addition to the traditional role of a BS, it also manages a unique feature of distributed sensing. This is needed to ensure proper PU protection and is managed by the BS, which instructs the various CPEs to perform distributed measurement of different TV channels. Based on the feedback received, the BS decides which steps, if any, are to be taken. Cleary, it is possible to have multiple WRAN cells that interfere. This is further aggravated because of the very large transmission area of those systems. Co-existence issues of WRAN cells are hence also addressed in the 802.22 standard.

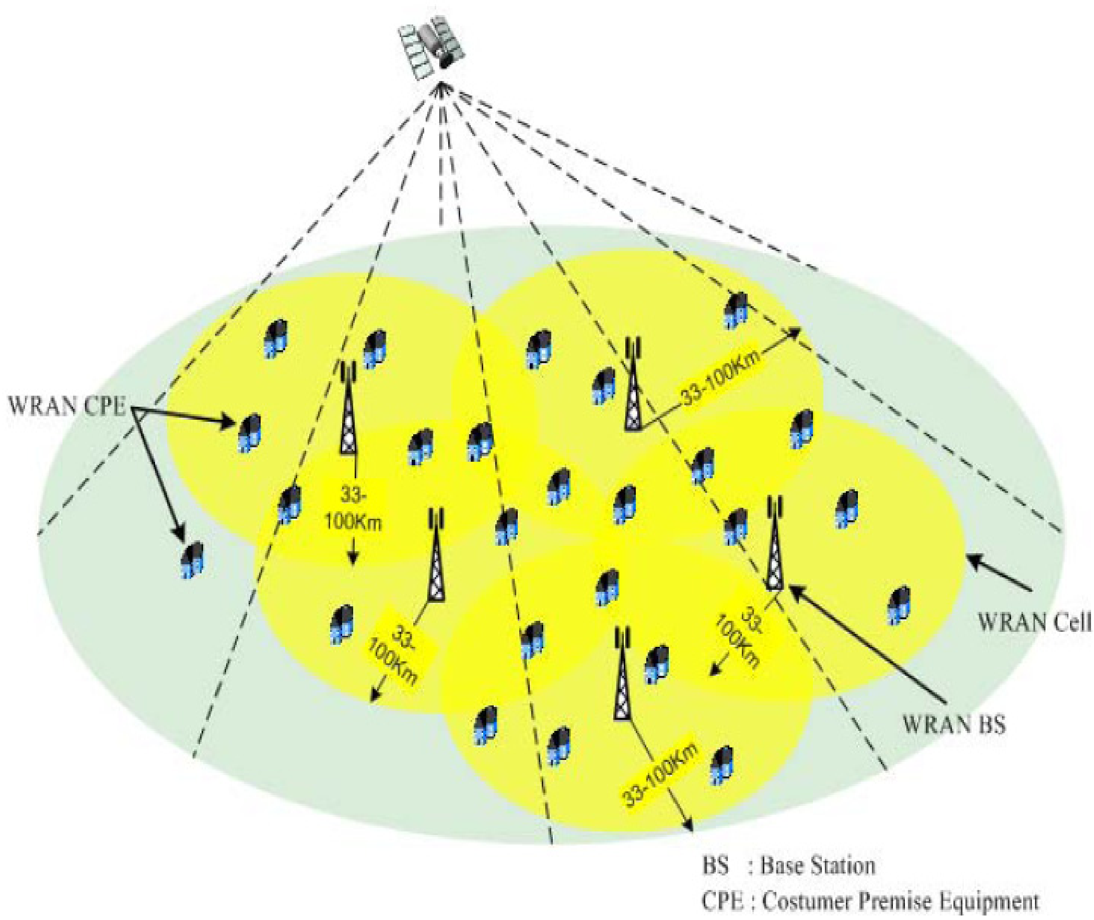

Figure 2-2: Exemplary WRAN deployment [15]

2.3.2 Service Capacity

Spectral efficiencies specified by the 802.22 system are in the range of 0.5 bit/(sec/Hz) up to 5 bit/(sec/Hz) [15]. For example, an average of 3 bits/(sec/Hz) could be achieved by a total PHY layer data rate of 18 Mbps over a 6 MHz TV channel. In downlink, WRAN supports a minimum data rate per CPE of 1.5 Mbps and a total of 12 simultaneous users. In the uplink direction, the standard specifies a peak throughput of 384 kbps, which is comparable to DSL services.

2.3.3 Service Coverage

As shown in Figure 2-1, the coverage area of WRANs is a much larger than today's networks. This is attributed to two reasons, higher power and the favorable propagation characteristics of TV frequency bands. The coverage radius of 802.22 WRAN can go up to 100 km (current specified coverage range is 33 km at 4 Watts CPE (EIRP)). However, this enhanced coverage range of WRAN offers unique technical challenges.

2.3.4 WRAN PHY and MAC Layers

The flexible and adaptable air interface is considered the distinctive and most critical requirement of WRAN. WRAN should be able to protect the PUs as well as satisfy the CPEs requirements in the co-existence environment. This section discusses the PHY and MAC layers design supporting such flexibility and adaptability, which provides the ideal foundation to spectrum sensing and co-existence issues later in chapter 3.

As depicted in Figure 1-5, spectrum sensing is a PHY layer task supported by spectrum management and spectrum mobility functions. These two functions also support link layer to perform spectrum sharing task. PHY and link layers are not independent from each other but there is cooperation results in cross-layer design. Sensing receiver and spectrum sensing techniques are discussed in sections 2.3 and 2.5, respectively.

2.3.4.1 PHY Layer

The functions of PHY layer in CR includes signal transmission and reception in additional to spectrum sensing. The PHY layer must be able to adapt to different conditions and also needs to be flexible for jumping from channel to channel without errors in transmission or losing clients (CPEs). To illustrate the challenge in designing CR PHY layer, Figure 2-3 depicts a particular example cited from [15] of what could be the pattern of TV channel occupancy by PUs over time and frequency. As it can be seen, spectrum holes (i.e., time during which a channel is vacant) which can be utilized by WRAN BSs and CPEs usually experience a random behavior which impacts the design of both MAC and PHY layers. In the specific case of the PHY layer, it needs to offer high performance while keeping the complexity low. In addition, an efficient spectrum sensing techniques is needed to exploit the available frequency to provide adequate performance, coverage and data rate requirements of the service. WRAN applications require flexibility on the downstream with support for variable number of users with possibly variable throughput. WRANs also need to support multiple access on the upstream. Multi-carrier modulation is very flexible in this regard [14], as it enables to control the signal in both time and frequency domains. This provides an opportunity to define two-dimensional (time and frequency) slots and to map the services to be transmitted in both directions onto a subset of these slots.

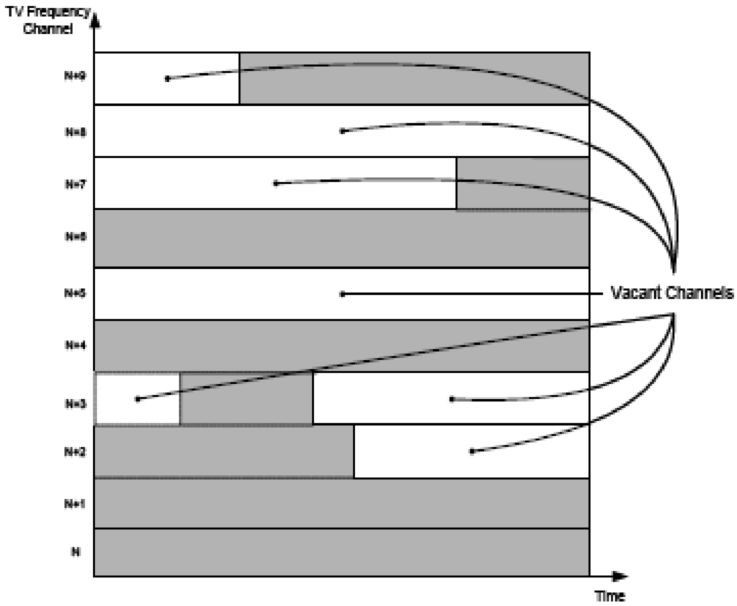

Figure 2-3: Example of TV band occupancy over time and frequency [15]

OFDMA is specified in 802.22 draft as a modulation technique for downstream and upstream links. Some technological improvements are added to OFDMA such as channel bonding which means aggregating contiguous or non-contiguous vacant TV channels [14]. In order to provide high flexibility in transmission in WRAN PHY layer, the BS must be capable of dynamically adjusting the bandwidth, modulation and coding, at least, on per CPE basis. For instance, CPEs may experience different Signal-to-Noise Ratio (SNR) due to their locations at various distances from the BS and; hence, OFDMA can be used to meet the requirements of each CPE as it allows efficient allocation of sub carriers.

2.3.4.2 MAC Layer

The MAC layer of WRAN is required to be highly dynamic in order to respond quickly to changes in the operating environment. Besides providing traditional MAC layer services, the 802.22 MAC layer is required to perform an entirely new set of functions for effective operation in the shared TV bands.

a) Super Frame and Frame Structure

Figure 2-4 [15] depicts the super frame structure implemented in the current 802.22 draft MAC. Every super frame sent by BS starts with special preamble and SCH (super frame control header). The super frames are sent through each and every TV channel (up to 3 contiguous) that is recognized as vacant and can be used for communication and meeting the incumbent protection requirements. CPEs tuned to any of these channels synchronize and receive the SCH, and thus are able to obtain all the information they need to associate with the BS. Multiple MAC layer frames are transmitted during the lifetime of a super frame, which may span multiple channels and hence provide better system capacity, range, multipath diversity, and data rate. However, for flexibility purposes; the MAC layer supports CPEs which are capable of operating on a single or multiple channels. During each MAC layer frame, the BS has the responsibility to manage the upstream and downstream directions, which may include ordinary data communication, measurement activities, co-existence procedures, etc. Each MAC layer has frame structure shown in Figure 2-5. As it can be seen, a frame consists of two parts: a downstream (DS) subframe and an upstream (US) subframe. As the data rate of the downstream and upstream are expected to be different, the boundary between the DS and US subframes is flexible. The downstream subframe consists of only one downstream PHY PDU with possible contention intervals for co-existence purposes. An upstream subframe consists of contention intervals scheduled for initialization (e.g., initial ranging), bandwidth request, UCS (Urgent Co-existence Situation) notification, and possibly co-existence purposes and one or multiple upstream PHY PDUs, each transmitted from different CPEs.

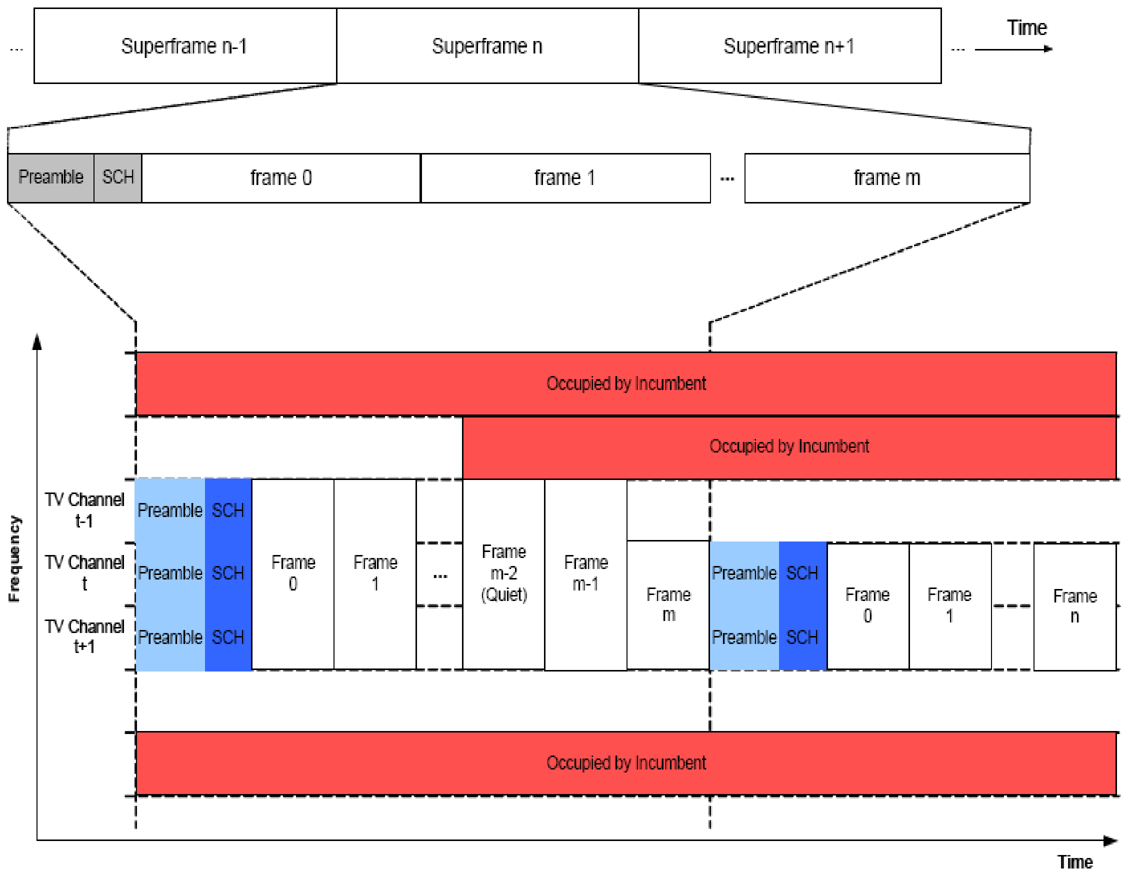

Figure 2-4: General super frame Structure [15]

b) Network Entry and Initialization

Generally, for centralized architecture such as WRAN where the CPEs operations are managed by a BS; network entry is a straightforward process in any MAC layer protocol. However, when operating in a shared band and on an opportunistic basis; network entry becomes challenged. Contrary to existing wireless technologies, there is no pre-determined channel available (channel may mean frequency, time, code, or any combination therein [14]) for a CPE to help find the BS. Thus, the MAC layer must be designed to address network entry, which is typically a simple procedure in existing wireless MAC layer protocols. However, In the 802.22 draft MAC, whenever a CPE starts up, it first scans (perhaps all) the TV channels and builds a spectrum occupancy map that identifies each channel whether incumbents or not. This information may be later conveyed to a BS and is also used by the CPE to determine which channels are vacant and, hence, use them to look for BSs. In those vacant channels, the CPE must then scan for SCH transmissions from a BS. The duration a CPE stays in a channel is at least equal to the super frame duration. Once the CPE receives the SCH, it acquires channel and network information that is used to proceed with network entry and initialization.

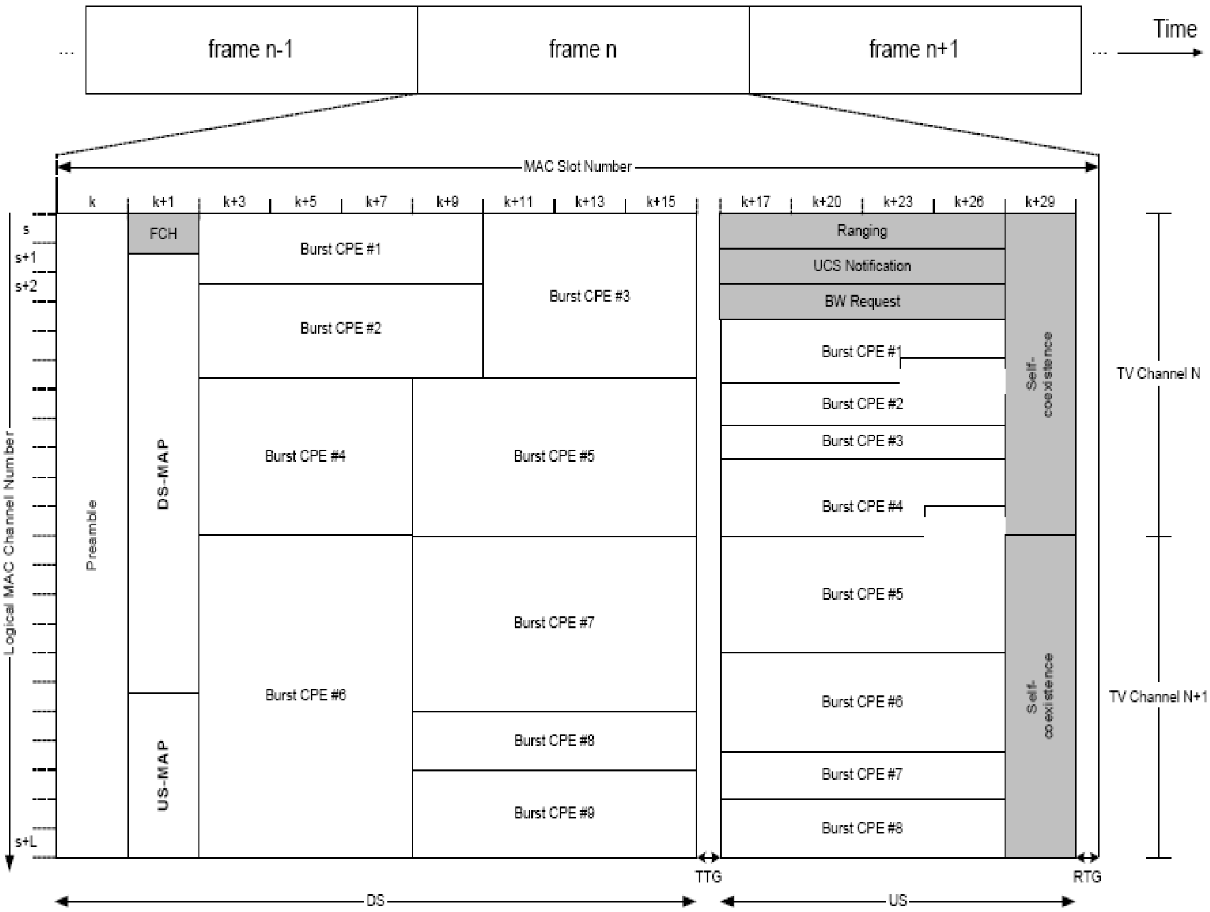

Figure 2-5: Time/Frequency structure of a MAC layer frame [15]

c) Measurements and Spectrum Management

Measurements and spectrum management related features are important portions of the 802.22 draft MAC. In an 802.22 cell, the BS instructs its associated CPEs to perform periodic measurement activities in order to operate without causing harmful interference to PUs. These measurements may be either in-band or out-of-band [15]. In-band measurement relates to the channel(s) used by the BS to communicate with the CPEs, while out-of-band correspond to all other channels.

To perform in-band measurements, the BS periodically quiets the channel, hence PU sensing can be carried out, which is not the case for out-of-band measurements. In order to ascertain the presence of PUs, 802.22 devices need to detect signals at very low SNR levels and with certain accuracy, and should be dynamically controlled by the BS. Since these measurements must be made in low SNR levels, it is assumed that the detection of TV signals is done in a non-coherent manner, that is, no synchronization is assumed. Measurements can take different amounts of time depending on the PU detection algorithms available at the various CPEs. In addition, the BS must indicate which CPEs must measure which channels, for how long, and with what probability of detection and false alarm. For best operation, the BS may not require every CPE to conduct the same measurement activities. Rather, it may incorporate algorithms that distribute the measurement load across CPEs and that use the measured values to obtain a spectrum occupancy map for the entire cell. The measured values by the CPEs must also be returned to the BS, which then analyzes them and if appropriate take actions.

The current 802.22 MAC layer draft provides support for all these aspects. It also incorporates a vast set of functions that allow it to efficiently manage the spectrum. Operations such as switch channels, suspend/resume channel operation, and add/remove channels are among the many actions the MAC layer may have to take in order to guarantee PUs protection and effective co-existence [9],[15].

d) Quiet Periods for PU Sensing

The current 802.22 MAC layer draft employs the quiet period mechanism for in-band channels as shown in Figure 2-6.   It consists of two stages which have different time scales: coarse sensing and fine sensing [14],[15].

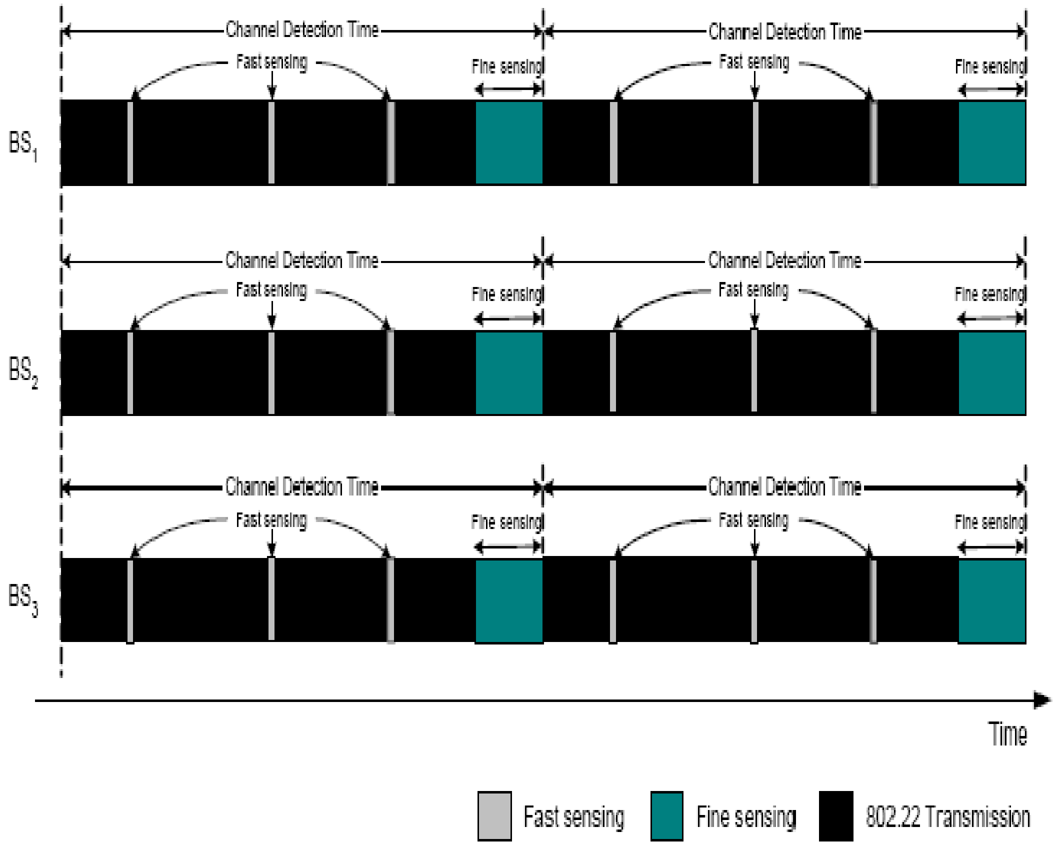

Figure 2-6: Two-stage quiet period mechanism [15]

1) Coarse Sensing

The coarse sensing stage consists of one or more fast sensing periods as depicted in Figure 2-6. During this stage, a fast sensing algorithm is employed (e.g., simple energy detection). Typically, this is done very fast (under 1 ms/channel) and hence can be made to be highly efficient. The outcomes of the measurements done by all CPEs and the BS during this stage are consolidated in the BS, who then decides on the need for the following fine sensing stage (discussed next). For example, if during the fast sensing stage it is concluded that energy in the affected channel is always below the threshold, the BS may decide to cancel the next scheduled fine sensing period.

2) Fine Sensing

The existence of this stage is dynamically determined by the BS based on the outcome of the previous fast sensing stage. During this stage, more detailed sensing is performed on the target channels. Typically, algorithms executed during this stage can take on the order of milliseconds for each single frequency channel, since they look for particular signatures of the PU transmitted signal. However, considering the fact that TV stations are not on the air frequently, this mechanism is highly efficient. Clearly, the possibility of having multiple overlapping WRAN BSs in operation in the same geographical region may undermine this two-stage quiet period approach. To overcome this problem, the WRAN system is able to dynamically synchronize multiple overlapping cells. Based on this, quiet periods of over lapping BSs are also synchronized resulting in the arrangement depicted in Figure 2-6. Hence, sensing can be made with high reliability.

2.4 Sensing Receiver

Spectrum sensing requires that a low SNR PU signal should be reliably detected. Low SNR means that PU might be below the noise floor. Under this case the received PU signal should be appropriately conditioned before detection processing. This section describes the architectures of sensing receiver of CR.

The general architecture of CR transceiver is depicted in Figure 2-7 [16]. It consists of two parts; RF front-end and baseband processing. These two parts are under control of MAC layer, hence they can be configured according to RF environment which is time-varying. For CR user transmission and reception, baseband processing functions include modulation/demodulation and encoding/decoding and other function of classical communication. For spectrum sensing, baseband processing has additional function for PU detection. This function does not need the demodulation and decoding of PU received signal but only needs the detection of its presence. This simplifies the sensing receiver and relaxes some functions such as synchronization. Signal processing for PU signals detection will be discussed in Chapter 3. This chapter discusses RFE of sensing receiver.

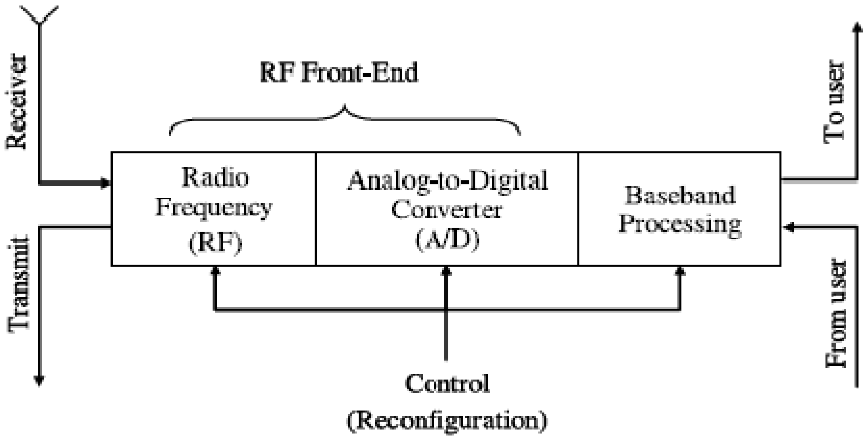

Figure 2-7: General sensing receiver architecture [16]

2.5 RF Front-End Architecture

The architecture of RFE of CR for spectrum sensing which is also called sensing radio depends on the availability of spectrum opportunities and the level of spectrum utilization in area of deployment of CR network. According to [18], there are three distinguishable regimes which lead to three different corresponding RFE architectures. These regimes are: low spectrum utilization, medium spectrum utilization, and high spectrum utilization.

2.5.1 Low Spectrum Utilization

In this regime there is no spectrum scarcity for CR network and spectrum utilization is below 10 %. Primary system usage of the spectrum in term of variation can be characterized as limited in temporal and spatial domains. An example of this regime is WRAN, in which there is abundance of spectrum in TV bands (approximately about 5 to 20 vacant TV channels) can be utilized by WRAN users. Also, TV broadcasting service can be described as static and continuous service with limited temporal and spatial variation. Figure 2-8 shows the RFE architecture for this regime. In order to tune over a band of interest, this architecture requires a wideband voltage controlled oscillator (VCO) and this is a main challenge in this architecture. On the other hand, down converted narrowband portion for this architecture makes it possible to use low speed A/D converter and fixed narrowband baseband for channel selection. Automatic gain control (AGC) is used to maintain the signal power at an appropriate level for a wide range of input signal levels.

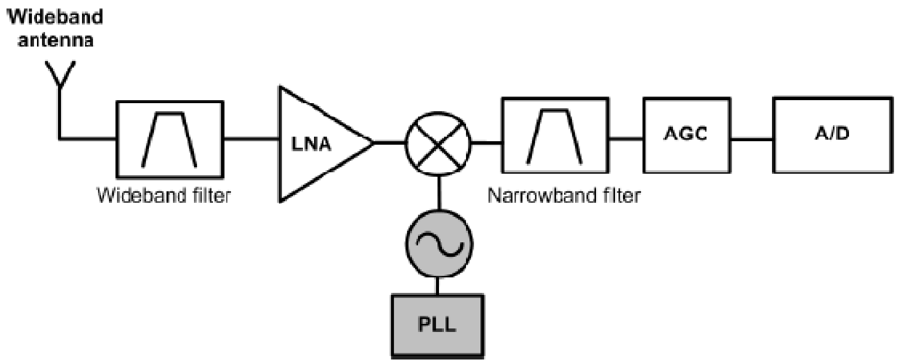

Figure 2-8: RFE architecture for low utilization regime [18]

2.5.2 Medium Spectrum Utilization

In this regime, the spectrum utilization is below 20 %, hence the probability to find spectrums holes decreases. In order to find more spectrum opportunities CR should have the ability to search over wide bands of spectrums in a short period of time. This necessitates wideband RFE architecture for sensing receiver. As proposed by [18], a parallel structure of narrowband RFE architectures is shown in Figure 2-9.

To improve the efficiency of this structure the bandwidth of the base band portion can be increased which required higher speed A/D converter (100-300 MHz) than low spectrum regime.

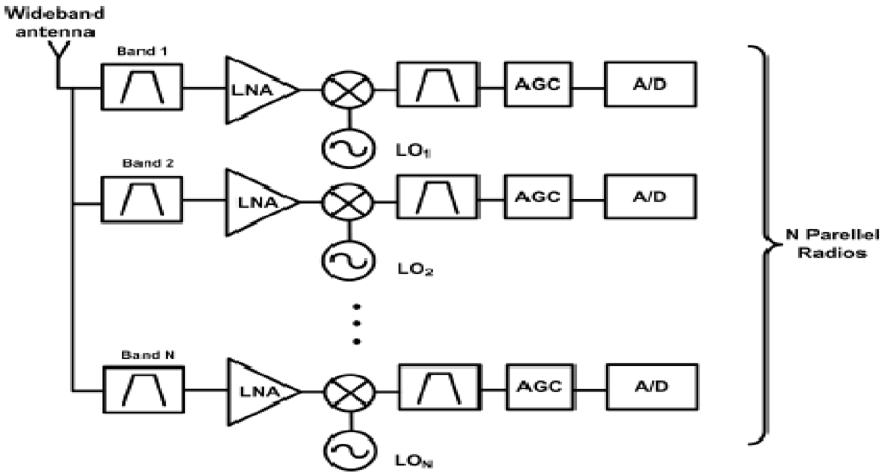

Figure 2-9: RFE architecture for medium utilization regime [18]

2.5.3 High Spectrum Utilization

The spectrum utilization in this regime is above 20 %, hence spectrum becomes a scarce resource. In addition, RF environment has different types of primary services and other competing cognitive networks which make it highly variable. In order to provide the required spectrum opportunities, a flexible RFE architecture can sense several GHz wide spectrums simultaneously. An architecture shown in Figure 2-10 with all circuitry should be wideband. This is a big challenge of multi-GHz speed sampling requirement for A/D converter which together with high resolution might be infeasible [19].

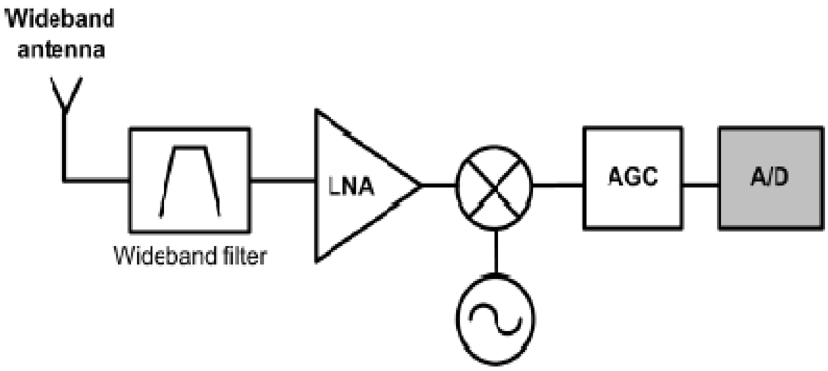

Figure 2-10: RFE architecture for High spectrum utilization regime [18]

2.6 Spectrum Sensing Techniques

Some of signal detection techniques for spectrum sensing have been proposed to enhance the probability of detection since the releasing of NPRM for TV bands and establishing of WRAN WG in 2004. As shown in Figure 2-11, the spectrum sensing techniques in general can be classified as transmitter detection, receiver detection or cooperative detection [9],[14].

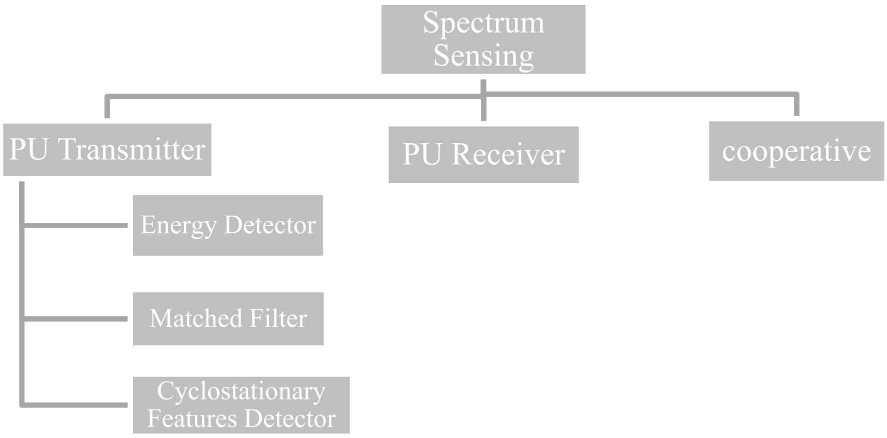

Figure 2-11: Classification of Spectrum sensing techniques

1. In transmitter detection techniques, the SU detects the PU transmitter signal. There are three well-known techniques of transmitter detection:

    - Energy detector: It is the simplest detector based on energy measurement. Energy detector has been studied extensively in context of spectrum sensing in the literature [20]-[25]. Energy detector can be applied to any type of signal and its performance was studied theoretically and supported with simulation results.

    - Matched filter: It is the optimal detector and requires perfect knowledge of PUs signals at the PHY and MAC layers. This coherent detection turns low SNR to high SNR, but if the prior knowledge is not accurate then the performance of matched filter will be poor. The application and analysis of matched filter for spectrum sensing are provided in [26],[27].

- Cyclostationary Features detector: This detector is based on cyclostationarity theory in [28]-[32]. Some works have been done which apply this type of detector to the problem of spectrum sensing.

    - [25] is the first work to suggest using cyclostationary features detector for spectrum sensing and it provides a general discussion of underlying theory that makes this detector possible for CR spectrum sensing. In addition, implementation issue is also discussed.

    - [33] applied and studied the performance of cyclostationary properties to detect ATSC Digital TV signal as the PU in the context of IEEE WRAN. ATSC is the TV standard replacing NTSC TV standard in North America.

    - [34] and [35] applied the cyclostationary features to spectrum sensing of DVB-T signal which is based on OFDM. Numbers of algorithms were developed based on cyclostationarity of OFDM such as pilot and cyclic prefix features. The performance of those algorithms was compared with energy detector.

    - [36] developed wireless microphone signal detector based on power spectral density (PSD) estimation. The performance of this detector was also studied.

    - [37] and [38] obtained spectral correlation of ATSC and wireless microphone with different SNRs. Contour figure was used to illustrate spectral correlation function. In this work, no spectrum sensing algorithm was developed based on the obtained spectral correlation.

2. For spectrum sensing based on receiver method, [39] proposed detecting local oscillator (LO) leakage power in the receiver which in WRAN CR is TV. The

drawbacks of this approach are that it requires long sensing time and a very short detection range. To solve these problem, [39] proposed using sensors close to each receiver in form of large sensor networks .

3. [40]-[42] studied cooperative sensing in which sensing information of multiple SUs are incorporated. This approach is theoretically more accurate than individual spectrum sensing because the probability of missed detection due to multipath fading and shadowing can be minimized. There are two types of cooperative sensing discussed in the literature. The first one is the centralized method in which all the sensing information from SUs are sent to the base station for final decision [40],[41]. The second one is the distributed method in which the sensing information are exchanged among SUs [42]. Generally cooperative sensing can be used with transmitter sensing or receiver sensing techniques.

Most of spectrum sensing literature focuses on transmitter sensing which is more challenging. In addition to the techniques shown in Figure 2-11, the following techniques also exist in the literature:

- Waveform-based sensing: In wireless systems, certain waveform patterns are used in the receiver to perform specific function such as synchronization or other purposes. Examples of these patterns include: preambles, midambles, pilot, or spreading sequences. [43] suggest using correlation between the received PU signal and known copy of itself. [26] applies this techniques to IEEE 802.11b and shows that while waveform based sensing requires short measurement time, it is susceptible to synchronization errors.

- Wavelet-based spectrum sensing: This method is efficient for wideband channels spectrum sensing. There are three approaches exist in the literature that use the concept of wavelet transform:

    1. [44] utilizes the wavelet as a powerful mathematical tool for analyzing singularity and edges. Hence, the wavelet transform is used to detect the edges in the PSD of the received PU. These edges correspond to transitions from an occupied band

to spectrum holes or vice versa. After indentifying the subbands within the wideband channel, the average PSD level is estimated in each subband which is used to decide if the subband can be considered as spectrum hole or not. This approach uses two wavelet solutions: wavelet modulus maxima and mutiscale wavelet products. The main disadvantage of this approach is the required high sampling rates in order to characterize the entire wide bandwidth.

2. [45] suggests an alternative approach for wideband spectrum sensing using wavelet. In this paper, discrete wavelet transform and discrete wavelet packet transform are used to decompose the PU signal into subbands. The number of decomposition levels determines the resulted number of subbands. After decomposition, the power of each subband can be calculated using the scaling and wavelet coefficients. This paper also proposes an algorithm by which the subbands can be sorted in the ascending order based on the calculated power. This technique is faster and less complex than the one suggested in [44].

3. In [46], a CR with a dual spectrum sensing mechanism is proposed. These dual stages provide coarse and fine sensing to meet the sensing speed and accuracy requirements. This technique uses the fact that wavelet transforms have various choices of basis functions. Certain types of those may have a resolution bandwidth as an additional freedom of design. Because the correlation between a given signal and wavelet basis waveform is used to obtain a wavelet transform coefficient, adjusting this wavelet's pulse width and its carrier frequency can represent spectral contents with scalable or multi-resolution. The spectral content of the received signal presented by the correlation values can be used to identify the

presence of the PU. This technique provides the flexibility to examine a wide band spectrum in fast coarse manner or in a fine manner if needed. In addition, the paper suggests an analog implementation for this technique to realize low power and real time operation.

- Filter bank- based spectrum sensing: instead of using wavelet, [47] uses filter bank for decomposition into subbands. Then, simple power detection is used based on PSD of the PU in each subband. The paper reduces the complexity of the filter banks architecture by using polyphase filters.
- Multitaper spectrum estimation is proposed in [13]. The proposed algorithms shown to be an approximation to maximum likelihood PSD estimator, and for wideband signals, it is nearly optimal. Although the complexity of this method is smaller than the maximum likelihood estimator, it is still computationally demanding.

In the light of this literature review, cyclostationary features detector is a promising spectrum sensing technique, as it can eliminate the effect of the noise and also reliably classify different signals. According to the best knowledge of the author, there is no work in the literature considering cyclostationary-based spectrum sensing for TV-PAL - the analog TV standard used in over 120 countries and territories. In addition, although cyclostationary features of wireless microphone signal was obtained in the literature there is no spectrum sensing algorithm and performance analysis were stated based on these features.

2.7 Summary

In this chapter, IEEE 802.22 WRAN standard is described. This includes its architecture and air interface functions of PHY and MAC layers. The three regimes of spectrum utilization and the corresponding proposed RFE in literature are also discussed. Spectrum sensing techniques are classified and the literature review of each technique is stated. To date, there is no work considering TV-PAL and wireless microphone spectrum sensing using cyclostationary features and this is the main research objective.

CHAPTER 3

SYSTEM MODEL: CO-EXISTENCE AND SPECTRUM SENSING BASED ON CYCLOSTATIONARY FEATURES

3.1 Introduction

Spectrum sensing is an important requirement of CR to adapt to the surrounding RF environment and to be aware of spectrum holes. This chapter provides a study of spectrum sensing model in the context of IEEE 802.22 WRAN as SU and TV-PAL and wireless microphone as PUs. Although spectrum sensing model is the main focus of this chapter, this cannot be done in isolation and a system model must precede it. This implies that it should additionally contain discussion about co-existence among SUs and PUs, RFE of SUs and calculation of prevailing noise. This chapter starts with co-existence scenario and calculation of signal power of PUs and co-existence radius of SUs. These calculations are done in worst co-existence scenario. Following this, RFE architecture is proposed for WRAN sensing receiver suitable for TV-PAL and wireless microphone. In order to calculate SNR, noise floor estimation and noise uncertainty modeling are also discussed.

Before discussing cyclostationarity-based spectrum sensing model which is the main focus of the chapter, the two conventional detection techniques are introduced. These techniques are energy detector and matched filter. However, as the main focus is on cyclostationary feature detector due to its ability to recognize the useful statistical features in the received signal, the discussion on cyclostationarity follows. In order to apply cyclostationarity-based spectrum sensing algorithms in chapter 4, the cyclostationary features of TV-PAL and wireless microphone are, therefore, first obtained in this chapter. Finally, an efficient implementation of cyclostationary feature detector is discussed and its computational complexity is analyzed in terms of the required number of multiplications and additions.

3.2 Co-existence in WRAN

WRAN with CR techniques incorporated by means of spectrum sensing and spectrum management, enable it to coexist and share spectrum efficiently with primary services. This section addresses the co-existence issue in WRAN to protect PUs and self-coexistence aspects.

3.2.1 Antennas

In WRAN system, each CPE is equipped with two separate antennas. The first one is a directional antenna used to communicate with BS. The second one is an omni-directional antenna used for spectrum sensing [14]. This antenna is recommended to be mounted outdoors to perform reliable spectrum sensing.

3.2.2 Co-existence with Analog TV-PAL and Wireless Microphone

The aim of this section is to find co-existence radius of WRAN's BS and CPE. The co-existence radius of SU is defined as the minimum distance between PU and SU beyond which no harmful interference is caused to PU by SU's transmission at PU licensed channel. In the context of TV-PAL, this thesis measures co-existence radius from TV-PAL transmitter to SU (CPE or BS). According to co-existence scenario, there are following three cases as shown in Figure 3-1.

- Case (1): The SU is outside its co-existence radius *D*, hence it can use PU's channel without causing harmful interference. In this case there is no restricted spectrum sensing requirements.

- Case (2): The SU is inside its co-existence radius *D*, hence it is required to sense the spectrum to determine the channels that are not being used by PU (spectrum holes). Restricted requirement of probability of detection is stated in this case to avoid harmful interference to the PU. Because of the relative nearness of SU to PU transmitter, the PU's signal strength results in reliable detection.

- Case (3): This is the worst case of the co-existence scenario in which the SU is at the edge of its co-existence radius. The SU needs to sense the spectrum to determine the spectrum holes. The weakness of PU's signal at that distance makes achieving the required probability of detection by WRAN quite challenging.

We will focus on the worst case to find the co-existence radiuses of CPE and BS of WRAN. Then, PUs signals power levels at co-existence radiuses are calculated. The minimum PU's signal power level at which the sensing algorithm should detect the presence of a primary signal with probability of detection specified by WRAN standard is called sensitivity requirement of the secondary system (the unlicensed system). These calculations will help develop big-picture of the challenge in spectrum sensing problem. Achieving the required sensitivity at co-existence radius can be considered ideal detector performance and, in this case, WRAN system can be deployed at co-existence radius. Otherwise, with non ideal detector WRAN system is deployed more inside co-existence area to get stronger PU's signal at CPE and BS.

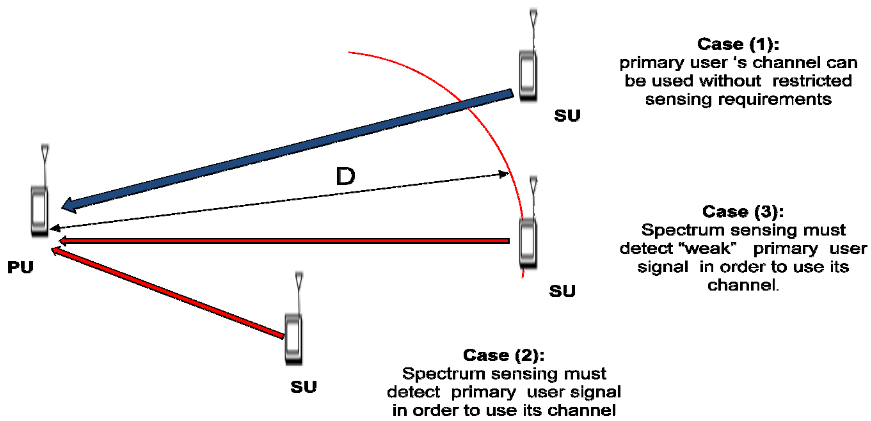

Figure 3-1: Co-existence scenario

Figure 3-2 shows the worst case scenario of WRAN, TV-PAL and wireless microphone. TV receiver is shown at the edge of broadcasting coverage area *R*. D_1 and D_3 are the co-existence radiuses of CPE with TV-PAL and wireless microphone, respectively. D_2 and D_4 are the coexistence radiuses of BS with TV-PAL and wireless microphone respectively. Table 3-1 shows default system parameters as specified by [48]-[50].

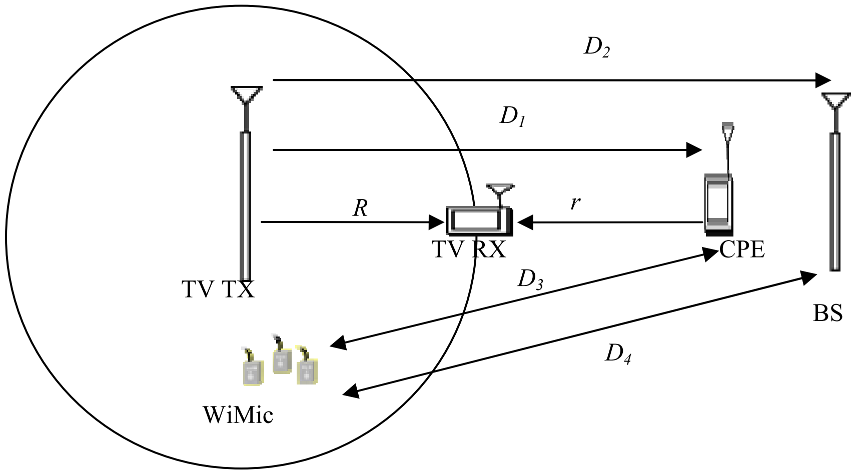

Figure 3-2: The worst case of coexistence scenario

Table 3-1: WRAN and PUs system parameters

WRAN parameters	
BS power (EIRP)	50 dBmW
CPE power (EIRP)	36 dBmW
BS Antenna height	75 m
CPE Antenna height	10 m
BS and CPE sensing Antenna gain G	0 dBi
BS Tx antenna Front-to-back ratio (F/B)	0 dB
CPE Tx antenna Front-to-back ratio (F/B)	16 dB
TV-PAL (VSB) parameters	
Transmitter power (ERP)	84.8 dBmW
Antenna height	300 m
Grade B contour	59 dB(uV/m)
Desired /undesired ratio (D/U)	40 dB
Front-to-back antenna ratio (F/B)	14 dB
Bandwidth	7 MHz in VHF 8 MHz in UHF
Wireless Microphone (FM) parameters	
Transmitter power (EIRP)	4 dBmW
Coverage area	100 m
Receiver sensitivity	-100 dBm
Noise figure	6 dB
Interference factor	-4 dB
Bandwidth	200 kHz

From these parameters, the distance R between the TV transmitter and grade B contour, using F(50,90) propagation curves [51], is 66.16 km. For the required D/U ratio of 40 dB, the minimum required distance r between CPE and TV receiver is calculated, using F(50,10) curve for the interference case, and it is 2.95 km. This results in D_1 to be 69.11 km. By finding D_1, F(50,90) curve can be used to predict the TV transmitter field strength at CPE and the corresponding power level was found to be -75.7 dBm. Repeating the previous steps for WRAN BS, the distance between TV transmitter and BS D_2 is 96.15 km and the received TV signal at BS is -89.3 dBm

In the case of wireless microphone, the radius of co-existence region of CPE (D_3), using the simplified path loss model, is 1.1 km and the wireless microphone signal power at that distance was calculated to be -122.9 dBm. For BS, the co-existence region radius D_4 is 2.62 km and the power of wireless microphone signal at that distance is -149.6 dBm.

If the CPE is inside its co-existence region, any transmission from CPE in same frequency band of the primary system will cause harmful interference to the primary receiver. The same applies to BS. WRAN transmission depends on the results of spectrum sensing, therefore, a significant probability of missed detection will cause harmful interference to the primary system. To avoid this case, spectrum sensing algorithm should be able to detect the presence of the primary signals with high probability of detection and by satisfying this condition WRAN system is allowed to co-exist with the primary systems. WRAN WG specifies the probability of detection, P_d, to be greater than 90% and the probability of false alarm, P_{fa}, to be less than 10%. Hence, a reliable spectrum sensing should achieve the required P_d inside the co-existence region.

As a summary, this scenario is the worst case that happens when the WRAN system is deployed near the edge of the services areas of the primary systems, which means the following:

- The WRAN may cause harmful interference to the primary systems.

- The primary signals are at their minimum levels at SU’s sensing receiver.

These calculations are summarized in Table 3-2.

Table 3-2: Summary of calculated co-existence radius and PUs signal power

PU	SU	Co-existence radius (km)	PU signal power level (dBm)
TV-PAL	WRAN BS	96.15	-89.3
TV-PAL	WRAN CPE	69.11	-75.7
WiMic	WRAN BS	2.62	-149.6
WiMic	WRAN CPE	1.1	-122.9

3.3 The Proposed RFE for TV-PAL and Wireless Microphone Spectrum Sensing

The WRAN CR can be described as low spectrum regime, hence narrowband architecture can be used for RFE of sensing receiver in this standard. The architecture shown in Figure 3-3 is proposed. After RFE and spectrum sensing stages, the detection results of spectrum sensing are transferred to MAC layer hence the available spectral resources can be identified for WRAN users’ transmission. Spectrum band for sensing is selected by a tunable RF filter under the control of MAC layer. The bandwidth of the RF filter is the same as the bandwidth of TV-PAL channel. In this thesis, PAL/I standard is used whose channel bandwidth is 8 MHz in UHF. Then, the RF band is down-converted using local oscillator at frequency of lower edge of RF band. The resulting lower side band extends from 0 MHz to 8 MHz and the upper side band is removed by low pass filter. A/D converter with sampling frequency of 16 MHz or more, with appropriate oversampling factor $\beta = \frac{f_s}{2BW}$ [19], can be used in this architecture. Oversampling offers more relaxing requirements of the anti-aliasing filters at the cost of a faster sampler. Finally, spectrum sensing processes the samples using appropriate detection algorithms.

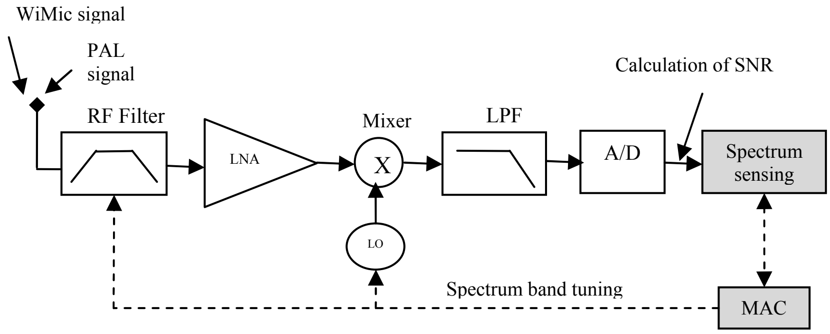

Figure 3-3: The proposed RFE for WRAN

3.3.1 Noise Floor Calculation

To be able to evaluate the performance of spectrum sensing techniques, noise power captured by the omni-directional sensing antenna from the surrounding environment as well as the noise introduced by RFE circuitry should be estimated. An estimation of noise power is given by [52],

$$N(dBmW) = -174 + NF + 10\log(BW) \quad (3.1)$$

where -174 is power spectral density of thermal noise in (dBmW/Hz), *NF* is the noise figure of low noise amplifier (dB) and *BW* is the bandwidth of spectrum band to be sensed . Using the values of *NF* = 11 dB [52] and TV-PAL/I channel bandwidth of 8 MHz, the noise power will be -94 dBmW . This value is used as the noise floor in performance evaluation of sensing algorithms in chapters 5.

3.3.2 Noise Uncertainty

It is well known that noise in communication systems is not only thermal noise introduced by the receiver but is an aggregation of various nearby unintended sources. Although the noise floor in the detector input has been calculated, the exact noise power is not known. This lack of knowledge of noise floor is called "noise uncertainty" [20]. There are many reasons for noise uncertainty [21]:

- Thermal noise variation because of temperature change.
- Low noise amplifier (LNA) gain variation according to temperature change.
- Calibration error.
- Error in estimate due to interference.

The first factor of thermal variation due to temperature change affects the value of noise power spectral density (PSD). Thermal noise PSD could be described by,

$$N_0 = K_b\, T \qquad (3.2)$$

where K_b is Boltzmann constant and T is the temperature in degree Kelvin. According to [20], to explain how the change in the temperature affects the N_0, let the temperature changes from T_1 to T_2 . Hence, the change in N_0 is given by,

$$\Delta N_0(dB) = 10\log(K_b\, T_2) - 10\log(K_b\, T_1) = 10\log(T_2) - 10\log(T_1) \qquad (3.3)$$

$$\Delta N_0(dB) = 10\log\left(\frac{T_2}{T_1}\right) \qquad (3.4)$$

If it is assumed that the room temperature raised from 300 ^{o}K to 320 ^{o}K, then the change in thermal noise PSD is,

$$\Delta N_0 = 10\log\left(\frac{320}{300}\right) = 0.28\, dB$$

The second factor of variation in LNA gain *(G_{LNA})* due to change in temperature can be illustrated for GaAs LNA operating at UHF band of TV broadcast that has change in gain about 0.01 dB/^{o}C [21]. To find LNA gain for 20 ^{o}C temperature change,

$$\Delta G_{LNA} = 20\times(0.01) = 0.2\, dB$$

The third factor of calibration error is the error during the initial calibration. For 1 ms samples used for calibrating power estimator, the standard deviation of the initial calibration is about 0.22 dB [22].

Combining these errors results in uncertainty of ±0.7 dB which can be rounded up to ±1 dB. However, it must be noted that this noise uncertainty may be much worse if the forth factor of interference from other SUs is also considered. In this thesis, noise uncertainties of 0, 1, 2 dB are used for performance evaluation.

3.3.3 Noise Uncertainty Modeling

In this thesis, robust statistics [53] is used to model the effects of noise uncertainty in spectrum sensing technique. This model could be considered as worst case approach. The PSD of the noise is given by,

$$N(dB/Hz) = N_0 + NF \pm \Delta \tag{3.5}$$

where Δ is noise uncertainty in dB. Robust statistics model use the upper limit of noise PSD which is,

$$N(dB/Hz) = N_0 + NF + \Delta \tag{3.6}$$

to calculate the probability of false alarm (P_{fa}). The lower limit of noise PSD which is,

$$N(dB/Hz) = N_0 + NF - \Delta \tag{3.7}$$

is used to calculate the probability of detection (P_d). Noise uncertainty is an important factor to evaluate the performance of any spectrum sensing technique.

3.4 Spectrum Sensing Model

If there is a specific band width [f_0 , f_N], the sensing problem is to detect whether a frequency band in that bandwidth is being used by PUs. Hence, the sensing issue can be formulated as a binary detection problem and the goal is to decide between the two hypotheses [53]; H_0 and H_1. H_0 means PU signal is absent and there is only noise at the input of the sensing receiver. H_1 means PU signal and noise are present at the input of sensing receiver. In other words;

$$y[n] = \begin{cases} w[n], & under\ H_0 \\ x[n] + w[n], & under\ H_1 \end{cases} \tag{3.8}$$

$$n = 1, \dots, N_s$$

where N_s is the number of the samples during observation time (i.e. sensing time), $y[n]$ is the received signal samples, $w[n]$ is AWGN with zero mean and variance σ_w^2. $x[n]$ is the PU signal which, in our case, is TV-PAL signal or wireless microphone signal.

The performance of a specific detector to distinguish between these two hypotheses is described by probability of missed detection P_{md} and probability of false alarm P_{fa},

$$P_{md} = P(D_0 \mid H_1) \tag{3.9}$$

$$P_{fa} = P(D_1 \mid H_0) \tag{3.10}$$

P_{md} means the cumulative probability that given hypothesis H_1, D_0 is detected. In other words, deciding that the PU signal is absent when, in fact, it is present in the band under sensing. Similarly, P_{fa} means the cumulative probability that given hypothesis H_0, D_1 is detected. In other words, deciding that the PU signal is present in the sensing band while, in fact, it is not. The trade off between P_{md} and P_{fa} has a vital role in CR. High P_{md} increases interference to PUs. On the other hand, high P_{fa}

would result in low spectrum utilization since false alarms increase the number of missed opportunities (i.e. missed spectrum holes). For WRAN 802.22 standard the requirements are $P_d \geq 90\%$ and $P_{fa} \leq 10\%$ [54]. The probability of detection, P_d, is defined by,

$$P_d = 1 - P_{md} \tag{3.11}$$

In this thesis, P_d and P_{fa} are used to evaluate the performance of the proposed spectrum sensing algorithms.

3.5 Energy Detector

Energy detector is the most basic and general detector [23],[24]. It is an optimal detector if the sensing receiver does not have enough information about the PU signal, hence it can be applied to any type of signal. Its test statistics is based on energy measurement and is given by,

$$TS = \frac{1}{N_s} \sum_{n=1}^{N_s} (y[n])^2 \tag{3.12}$$

which is measured and averaged over N_s samples. To apply this test statistics, the PU signal occupying bandwidth B is first downconverted and sampled at the Nyquist rate $f_s = 2B$. The test statistics is compared with a threshold, λ, to decide whether a PU is present or not. For large number of samples N_s [23], P_d and P_{fa} are given by,

$$P_{fa} = Q\left(\frac{\frac{\lambda}{\sigma_w^2} - N_s}{\sqrt{2N_s}} \right) \tag{3.13}$$

$$P_d = Q\left(\frac{\frac{\lambda}{\sigma_w^2 + \sigma_x^2} - N_s}{\sqrt{2N_s}} \right) \tag{3.14}$$

where $Q(x)$ is the right-tail probability or also called complementary cumulative distribution function. For given $\gamma = SNR = \frac{\sigma_x^2}{\sigma_w^2}$, the minimum number of samples N_s required to achieve the target P_d and P_{fa} is given by [53],

$$N_s = 2\left[\left(Q^{-1}(P_{fa}) - Q^{-1}(P_d)\right)\gamma^{-1} - Q^{-1}(P_d)\right]^2 \tag{3.15}$$

While energy detector is simple and can be implemented easily and efficiently, it has some disadvantages stated hereunder:

- its performance is susceptible to noise uncertainty [20].
- it can not recognize signal features, hence it can not be used to distinguish between different signals types.
- it is not effective for signals whose signal power has been spread over wideband.

In this thesis, the performance of the proposed cyclostationary–based spectrum sensing is compared with energy detector in the context of WRAN requirements for TV-PAL and wireless microphone PU signals.

3.6 Matched Filter

Matched filter detector is considered an optimal detector [53], since it maximizes the received SNR. It is a coherent detector and demodulation of a PU signal is required, hence PHY and MAC layers of CR should have a-priori knowledge of the received PUs signals. This knowledge includes modulation type and order, pulse shaping, packet format and other information needed for demodulation. In addition, timing and carrier synchronization with PU signal are also required for demodulation process. The matched filter performs poorly if this information about PUs signals is not accurate.

The main advantage of the matched filter is that high processing gain is achieved within less time. However, in the context of CR spectrum sensing the significant drawback of matched filter is that a dedicated receiver is needed for each primary licensed system [25].

3.7 Cyclostationary Features of Primary Users

In this section, the theory of cyclostationarity is introduced and the motivation behind using the theory in the context of spectrum sensing is discussed. It is followed by obtaining the said cyclostationary features of TV-PAL and wireless microphone that, to best of our knowledge, are obtained for the first time in this thesis. These features are used for developing detection and classification algorithms – algorithms that are proposed in chapter 4**.**

3.7.1 Cyclostationarity Theory

Data symbols are modeled as stationary random process. However, communication signals are in general coupled with carriers, pulse trains, repeating sequences or cyclic prefixes or other intended signals that causes hidden periodicity. These communication signals have distinctive features and are classified as cyclostationary random processes [25]. The signal, $x(t)$, is defined to be a second order wide sense cyclostationary if its mean and autocorrelation, are periodic with some period T_o:

$$\mu_x(t) = \mu_x(t + T_o) \tag{3.16}$$

$$R_x(t, \tau) = R_x(t + T_o, \tau) \tag{3.17}$$

Since the autocorrelation function is periodic, it can be represented by Fourier series [28]:

$$R_x^{\alpha}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{T} x\left(t + \frac{\tau}{2}\right) x\left(t - \frac{\tau}{2}\right)^{*} e^{-j2\pi\alpha t}\, dt \tag{3.18}$$

$R_x^{\alpha}(\tau)$ is called cyclic autocorrelation function (CAF) which is used to examine the second order periodicity of the cyclostationary signals. If the signal is cyclostationary with period T then cyclic autocorrelation has component at $\alpha = 1/T$. Cycle autocorrelation is a time domain transform; its frequency domain equivalent can be found by establishing Wiener relationship:

$$S_x^{\alpha}(f) = F\{R_x^{\alpha}(\tau)\} = \int_{-\infty}^{+\infty} R_x^{\alpha}(\tau)\, e^{-j2\pi f\tau}\, d\tau \qquad (3.19)$$

$S_x^{\alpha}(f)$ is called cyclic spectral density (CSD) or spectral correlation function (SCF). Obviously, SCF is a 2-D symmetric transform that consists of two variables, the cyclic frequency α and the spectral frequency f. Power spectral density (PSD) is a special case of SCF when $\alpha = 0$:

$$PSD = S_x^{0}(f) \qquad (3.20)$$

In the following subsections TV-PAL and wireless microphone as PUs signals are studied generally and then specifically in the context of cyclostationary features that can be used for detecting them in low SNR under noise uncertainty.

3.7.2 TV-PAL Signal

PAL, short for Phase Alternating Line, is a color-encoding system used in broadcast television system [55] in large parts of the world. Other common analog television systems are Sequential Color with Memory (SECAM) and National Television System Committee (NTSC). The name "Phase Alternating Line" describes the way the phase of part of the color information on the video signal is reversed with each line, which automatically corrects phase errors in the transmission of the signal by cancelling them out. Lines where the color phase is reversed compared to NTSC are often called PAL or phase-alternation lines, which justifies one of the expansions of the acronym, while the other lines are called NTSC lines. The full discussion of TV-

PAL system aspects is available in [56]. The various components of the composite transmitted signal by TV-PAL station are given below.

.

- *Color camera output*: It is the full information of the brightness and hue of various colors present in the scene being televised. This information is represented by *R, G* and *B* color voltages developed by the color camera. These are gamma corrected to account for non-linear characteristic of the picture tube.

- *Luminance (Y) signal*: It is the same luminance signal as of black and white camera. It carries brightness information of the picture.

- *Color-difference signals*: They are generated by the matrix circuit and consist of (*B-Y*) and (*R-Y*). Then, they are multiplied by weighting factors to prevent excessive over-modulation of the picture carrier. Their bandwidth is restricted to about 1.5 MHz because of the limitation of the eye to perceive finer details in color. In some PAL color versions a total bandwidth of 2 MHz is allowed.

- *Chrominance signal*: It is quadrature amplitude modulated subcarrier (also called color subcarrier f_{cs}) using weighted color–difference signals. Its bandwidth is also limited by filtering out higher harmonics at the output of quadrature modulator and combining circuits. Chrominance information is added to the luminance video signal *Y* by frequency interleaving to form a composite video baseband signal.

- *Line sync pulses*: These are 4.7 μs pulses, part of the 12 μs line blanking period. These pulses occur at same line frequency which is 15625 Hz. Line sync pulses are added to the *Y* signal.
- *Field sync pulses*: These are 160 μs blanking period after each scanning field. It occurs at a frequency of 50 Hz. These pulses are also added to the *Y* signal before combining it with the chrominance signal.

- *Color burst*: It is 9 to 11 cycles at the frequency of color subcarrier at the black porch of each line blanking pulse for synchronizing the color subcarrier generator at the TV receiver. Color burst also contains an identification signal at half the line frequency (about 7.8 kHz) to identify NTSC and PAL lines. The color burst signal is added to chrominance signal.

- *Sound signal*: This signal represents the sound information associated with the scene. It is amplified and frequency modulated with bandwidth limited to 15 kHz.

- *Picture carrier* (f_{pc}): It is VHF/UHF sinusoidal signal AM-VSB modulated by the composite signal of luminance signal, chrominance signal, line sync, field sync and color burst.

- *Sound carrier* (f_{ac}): For transmission purposes, the sound signal is frequency modulated with channel sound carrier. Then the two modulated signals, the picture carrier and sound carrier, are combined and sent to antenna array through a coaxial cable. The radiated array is usually located on a high tower, hill or a tall building.

PAL system has various identification standards schemes with differences relating to the audio frequency and channel bandwidths. In this thesis, the focus will be on PAL/I standard, which is used in UHF with bandwidth of 8 MHz. The video bandwidth (*Y* signal) of PAL/I is 5.5 MHz. The color subcarrier and sound carrier located at 4.43361875 MHz and 6 MHz away from the picture carrier respectively. The spectrum of PAL/I system is shown in Figure 3-4. The vestigial sideband is 1.25 MHz and the bandwidth of the color-difference signal is approximately 2 MHz [56].

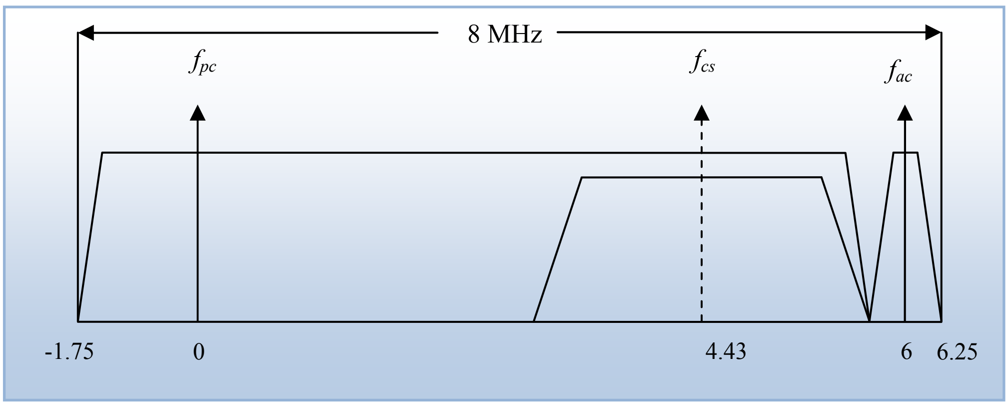

Figure 3-4: The spectrum of PAL/I

The transmitted PAL signal can be represented by the following equation [56],

$$x_{PAL}(t) = \{[A_P + v(t)]\cos(2\pi f_{pc}t)\} * h_{VSB}(t) + A_a\cos[2\pi f_{ac}t + 2\pi K_{f1}\int_0^t a(\lambda)d\lambda\,] \tag{3.21}$$

where the first term represents VSB-AM modulated picture signal, and the second term represents the FM modulated audio signal. $A_P\cos(2\pi f_{pc}t)$ and $A_a\cos(2\pi f_{ac}t)$ are picture carrier and audio carrier respectively. $v(t)$ is the composite video baseband signal of luminance and chrominance signal. It is important to mention that the color subcarrier f_{cs} included in $v(t)$ is suppressed by using push-pull quadrature modulator. $h_{VSB}(t)$ is the impulse response of the vestigial side band filter used to attenuate part of lower side band. $a(t)$ is the audio information picked by camera microphone and K_{f1} is the frequency modulation index.

3.7.3 Wireless Microphone Signal

A wireless microphone is an audio transmission service. As the names implies, the microphone is used without a physical cable connecting it to the amplifying equipment or sound recording which allows greater freedom of movement for the speaker. The main application of a wireless microphone is to provide real-time high quality audio transmission over short distances up to 300 m. Wireless microphones are classified as low power auxiliary stations and are considered as licensed secondary of the TV spectrum. Wireless microphones operate on vacant TV channels based on frequency planning and coordination. Many older wireless microphone systems operate in the VHF and most of modern systems operate in UHF TV band [57]. The maximum transmission power depends on the operating band; for VHF it is 50 mW and 250 mW for UHF [58].

Almost all wireless microphone systems use wideband FM modulation with bandwidth of 200 kHz. The wireless microphone signal can be represented as FM signal given by,

$$x_{FM}(t) = A_c \cos[2\pi f_c t + 2\pi K_{f2} \int_0^t m(\lambda) d\lambda\,] \qquad (3.22)$$

where $A_c \cos(2\pi f_c t)$ is the carrier frequency of wireless microphones transmitter in TV spectrum, $m(t)$ is the baseband speech signal and K_{f2} is the frequency modulation index.

3.7.4 Spectral Correlation Function of The Primary Signals

The most obvious cyclostationary features of TV-PAL and wireless microphone result from the carriers signal coupled with these signals. For a sinusoidal signal at frequency of f_c, $A_c \cos(2\pi f_c t\,)$, its cyclostationarity can be found by using this in CAF given in Eq.(3.18),

$$R_x^{\alpha}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_T cos\left[2\pi f_c\left(t + \frac{\tau}{2}\right)\right] cos\left[2\pi f_c\left(t - \frac{\tau}{2}\right)\right] e^{-j2\pi\alpha t}\ dt \qquad (3.23)$$

When $\alpha = 0$, Eq.(3.23) becomes the conventional autocorrelation of sinusoidal signal which has peaks at,

$$\tau = n\frac{1}{2f_c}\ , \qquad n = 0, \pm 1, \pm 2, \pm 3, .. \qquad (3.24)$$

In order to simplify the explanation, $\tau = 0$ in Eq.(3.23) is assumed which leads to,

$$R_x^{\alpha}(0) = \lim_{T\to\infty} \frac{1}{T} \int_T [cos(2\pi f_c t)]^2\ e^{-j2\pi\alpha t}\ dt$$

$$= \lim_{T\to\infty} \frac{1}{T} \int_T \frac{cos\,2(2\pi f_c t) + 1}{2}\ e^{-j2\pi\alpha t}\ dt \qquad (3.25)$$

This can be seen as the Fourier transform of $\frac{\cos 2(2\pi f_c t)+1}{2}$, which leads to peaks at $\alpha = 0$ (i.e. the DC component) and $\alpha = \pm 2f_c$. SCF, $S_x^\alpha(f)$,is found by taking Fourier transform of $R_x^\alpha(\tau)$ as in Eq.(3.19). $R_x^\alpha(\tau)$ is periodic in terms of τ with period ${}^{1}\!/_{f_c}$ according to Eq.(3.24). Hence, $S_x^\alpha(f)$ has peaks at $f = \pm f_c$, in addition to the peaks at $\alpha = 0$ and $\alpha = \pm 2f_c$.

This case applies to wireless microphone signal which has one carrierf_c. For TV-PAL signal there are two carriers; picture carrier (f_{pc}) and sound carrier (f_{ac}). By following the same previous steps for one carrier, CAF is found by,

$$R_x^\alpha(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_T \left[\cos 2\pi f_{pc}\left(t + \frac{\tau}{2}\right) + \cos 2\pi f_{ac}\left(t + \frac{\tau}{2}\right)\right] \left[\cos 2\pi f_{pc}\left(t - \frac{\tau}{2}\right) + \cos 2\pi f_{ac}\left(t - \frac{\tau}{2}\right)\right] \; e^{-j2\pi\alpha t} \; dt \tag{3.26}$$

When $\alpha = 0$, Eq.(3.26) becomes the conventional autocorrelation of summation of two sinusoidal carriers which has peaks at,

$$\tau = n\frac{1}{2f_{pc}}, \qquad n = 0, \pm 1, \pm 2, \pm 3, .. \tag{3.27a}$$

and,

$$\tau = n\frac{1}{2f_{ac}}, \qquad n = 0, \pm 1, \pm 2, \pm 3, .. \tag{3.27b}$$

As previous, $\tau = 0$ is assumed which simplifies Eq. (3.26) to,

$$R_x^\alpha(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_T [\cos 2\pi f_{pc} t]^2 + 2[\cos 2\pi f_{pc} t]\,[\cos 2\pi f_{ac} t] + [\cos 2\pi f_{ac} t]^2 \;\; e^{-j2\pi\alpha t} \; dt \tag{3.28}$$

Using trigonometry to evaluate this Fourier transform results in peaks at

$\alpha = 0,\ \pm 2f_{pc},\ \pm 2f_{ac},\ \pm(f_{pc} + f_{ac}),\ \pm(f_{pc} - f_{ac})$. Finding SCF by applying Eq. (3.19) and using [28],[31], we get peaks at following locations in terms of (f, α): $(\pm f_{pc}, 0), (\pm f_{ac}, 0),\ (0, \pm 2f_{pc}),\ (0, \pm 2f_{ac}),\ \left(\pm \frac{f_{pc}-f_{ac}}{2}, \pm(f_{pc} + f_{ac})\right)$ and $\left(\pm \frac{f_{pc}+f_{ac}}{2}, \pm(f_{pc} - f_{ac})\right)$. The peaks at non-zero value of α are called the cyclostationary features of the signal.

3.7.5 Cyclostationarity-Based Spectrum Sensing Model

The motivations for utilizing cyclostationarity for CR spectrum sensing are that, first, the white Gaussian noise is a stationary process and contributes only to PSD of the received signal, hence for $\alpha \neq 0$, SCF of AWGN is ideally zero. This makes cyclostationary features detector robust against noise uncertainty. In this thesis, the noise is assumed to be AWGN, but other sources of interference may follow other distribution model which requires further analysis and assumptions. Second, different signals have distinctive cyclostationary features and consequently distinctive SCFs which could be used for signals classification. By computing the SCF of the received signal $y(t)$, provided that the PU signal $x(t)$ is cyclostationary and has nonzero component at some nonzero cyclic frequency, the detection hypotheses in Eq. (3.8) can be written as,

$$S_y^{\alpha}(f) = \begin{cases} S_w^{\alpha}(f), & under\ H_0 \\ S_x^{\alpha}(f)\ +\ S_w^{\alpha}(f), & under\ H_1 \end{cases} \tag{3.29}$$

As AWGN has no cyclostationary features, so evaluating SCF of the received signal at $\alpha \neq 0$ the binary hypotheses is converted to,

$$S_y^{\alpha \neq 0}(f) = \begin{cases} 0, & under\ H_0 \\ S_x^{\alpha \neq 0}(f)\ , & under\ H_1 \end{cases} \tag{3.30}$$

In these hypotheses the effect of AWGN is eliminated. This illustrates the advantage of using cyclostationary features detector in low SNR with noise uncertainty. In contrast, power detector measurement according to Parseval's theorem [59] is given by,

$$power = \lim_{T\to\infty}\frac{1}{T}\int_{T}[y(t)]^2\ dt \quad = \quad \lim_{T\to\infty}\frac{1}{T}\int_{-\infty}^{+\infty}[Y_T(f)]^2\ df$$

$$= \int_{-\infty}^{+\infty} PSD\ df$$

$$= \int_{-\infty}^{+\infty} S_y^0(f)\ df \qquad (3.31)$$

Hence, spectrum sensing based on power detector (or energy detector) is highly susceptible to unknown or changing noise levels.

3.8 Computational Complexity of Cyclostationary Features Detector

In addition to Eq. (3.19), cyclostationary features can be also obtained equivalently by:

$$S_x^\alpha(f) = \lim_{\Delta f\to 0}\lim_{\Delta t\to\infty}\frac{1}{\Delta t}\int_{-\Delta t/2}^{\Delta t/2}\Delta f\, X_{\frac{1}{\Delta f}}\left(t, f+\frac{\alpha}{2}\right).X_{\frac{1}{\Delta f}}^*\left(t, f-\frac{\alpha}{2}\right)\ dt \qquad (3.32)$$

where $X_{T_W}(t,v)$ is short time Fourier transform (STFT) with window size of $T_W = {}^1/_{\Delta f}$ and given by:

$$X_{T_W}(t,v) = \int_{t-{}^{T_W}/_2}^{t+{}^{T_W}/_2} x(u)\, e^{-j2\pi v u}\ du \qquad (3.33)$$

The derivation of Eq. (3.32) from Eq. (3.19) is developed in [28],[61]. Put here accurately, Eq. (3.19) is cyclic spectral density, CSD, and Eq. (3.32) is spectral correlation function, SCF, and the derivation states that, as Δf goes to 0 and observation time (Δt) goes to infinite; SCF approach CSD. In practice, the CSD must be estimated because the signals being considered are defined over a finite time interval (Δt), and therefore the cyclic-spectral density cannot be measured exactly. Describing Eq. (3.32) and Eq. (3.33) in discrete form for N observation samples and N' STFT window yields:

$$S_x^{\beta}(k) \triangleq \frac{1}{N}\sum_{n=0}^{N-1}\left[\frac{1}{N'} X_{N'}\left(n, k + \frac{\beta}{2}\right) X_{N'}^{*}\left(n, k - \frac{\beta}{2}\right)\right] \tag{3.34}$$

$$X_{N'}(k) \triangleq \sum_{n=0}^{N'-1} w[n]x[n] \; e^{\frac{-j2\pi kn}{N'}} \tag{3.35}$$

where k and β are the discrete form of spectral frequency (f) and cyclic frequency (α), respectively. In Eq. (3.35), $w[n]$ is data taper window of size N' used for STFT. [60] describes a computationally efficient realization structure for Eq. (3.34) which is shown in Figure 3-5. This architecture is based on Fast Fourier Transform (FFT) and it is known as FFT Accumulation Method (FAM).

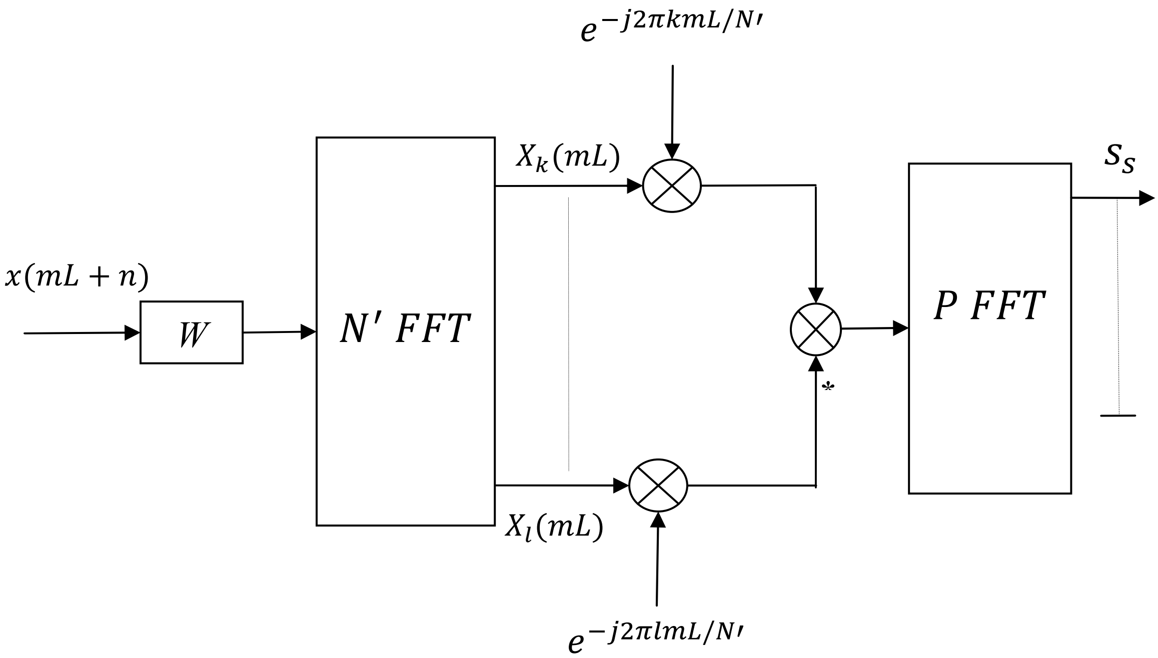

Figure 3-5: FFT accumulation method (FAM) [60]

This architecture consists of three basic stages:

1. Computation of the complex demodulates: In this stage the N input samples are channelized into N' parallel samples (window size of STFT) with overlap factor L of the sliding window. Then N'-Point FFT is used to calculate STFT followed by base band frequency-downshift translation sections.
2. Forming the product sequences between each one of the complex demodulates and the complex conjugate of the others.
3. Smoothing of the product sequences over the total observation samples N using P-point FFT.

The appropriate choice of FFT points depends on the required spectral and cyclic frequencies resolution Δf and $\Delta\alpha$, respectively. The relationship between FFT and the required resolution for given sampling frequency f_s is given by:

$$N' = \frac{f_s}{\Delta f} \tag{3.36}$$

$$P = \frac{f_s}{\Delta\alpha . L} \tag{3.37}$$

The relationship between N and P is:

$$N = P \times L \tag{3.38}$$

The correspondence between the FFT indices and certain values of f and α in SCF domain in the output are given as follows [61]:

$$S_s \approx S_x^{\alpha_0}(f_0) \tag{3.39}$$

where

$$f_0 = \frac{k + l}{2N'} \tag{3.40}$$

and

$$\alpha_0 = \frac{k - l}{N'} + \frac{P}{N} \tag{3.41}$$

The complexity of FAM in terms of the required additions and multiplications of different stages is shown in Table 3-3 [60]. The table shows the complexity in terms of N' and P for each stage. For the first three stages, the complexity depends on N', while the complexity of the last two stages depends on P.

Energy detector is well known for its simplicity in term of implementation and the computations required. Energy detector requires $4N$ real multiplications and $2(2N-1)$ real additions [62]. The additional complexity of FAM compared with energy detector comes with superior performance of cyclostationarity detector as a spectrum sensing and classification technique.

For example, using Eq. (3.36) and Eq. (3.37) for $f_s = 4000\ Hz$, $\Delta f = 128\ Hz$, $\Delta\alpha = 64\ Hz$ and $L = 8$, N' and P can be calculated and they are $N' = 32$ and $P = 8$ (both are approximated to be power of two). Using Table 3-3 for these calculated values, the real multiplications required for the five stages are 560 and the real additions are 632. While for energy detector, the required real multiplications are 256 and the real additions are 254.

Table 3-3: Complexity summary of FAM

Func. / Ops.	Window	N' FFT	Down Conversion	Correlation Multiplication	P FFT
Real multiplications	N'	$2N' \log_2 N'$	$4N'$	$4P$	$2P \log_2 P$
Real additions	None	$3N' \log_2 N'$	$2N'$	$2P$	$3P \log_2 P$

3.9 Summary

In this chapter, a complete system model within the co-existence framework of PUs and SUs is discussed and co-existence radiuses of SUs and the PUs signal power levels are calculated for worst-case scenario. Noise floor calculation and noise uncertainty are described for the proposed RFE of sensing receiver. Robust statistics are used in this thesis to model noise uncertainty to evaluate the proposed spectrum sensing algorithms.

Cyclostationarity theory is introduced followed by the cyclostationary features of TV-PAL and wireless microphone signals. These primary signals are shown to have distinctive features related to carrier signals. The novelty of this thesis, is converting detection domain from PSD to CSD in the context of TV-PAL and wireless microphone which enables higher probability of detection and classification ability. Finally, the implementation of cyclostationary feature detector using FAM technique is studied in terms of its computational complexity. While energy detector has the advantage of simple implementation, the gained performance of cyclostationarity detector as discussed in Chapter 5, is worth the added complexity. In the next chapter, spectrum sensing and classification algorithms based on the obtained features will be proposed.

CHAPTER 4

FEATURES DETECTION AND CLASSIFICATION ALGORITHMS

4.1 Introduction

In the last chapter, theory of cyclostationarity is explained and applied to TV-PAL and wireless microphone signals. In this chapter, the cyclostationary features, obtained in the last chapter, are used to develop spectrum sensing algorithms. In addition, an approach for primary signals classification incorporated into spectrum sensing algorithm is proposed. The first section finds spectral frequencies and cyclic frequencies of SCF of the downconverted received PUs signals. Following this, wireless microphone and TV-PAL spectrum sensing algorithms are explained and their flow charts are given. Then we discuss how these distinctive cyclostationary features are used for classification of PUs signals. In order to assess the performance of these algorithms, the methodology to obtain and evaluate the performance is explained. This is used to obtain the performance results in Chapter 5.

4.2 Cyclostationary Features of Down Conversion Spectrum

The proposed RFE of sensing receiver shown in Figure 3-3 is used for conditioning the received signal. This includes two functions; the first one is spectrum band selection by a tunable RF filter under the control of MAC layer. The bandwidth of the RF filter is the same as the bandwidth of TV-PAL channel which is 8 MHz for PAL/I standard in UHF used in this work. The second function is down conversion of the selected band. Because the goal is to detect the presence of the PUs not to demodulate their signals, it is more appropriate using local oscillator at frequency of lower edge of RF band to reserve the whole 8 MHz TV channel. Figure 4-1 shows the down converted TV-PAL channel which extends from 0 to 8 MHz, instead of -1.75 to 6.25 MHz in Figure 3-4.

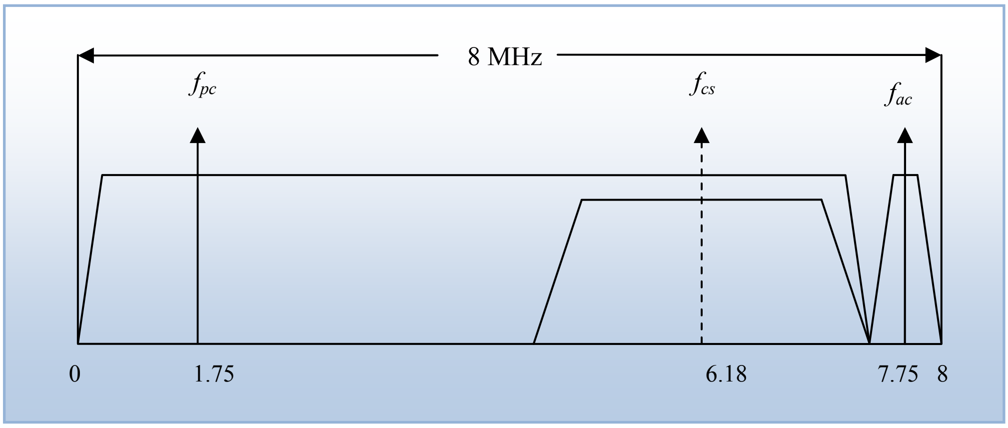

Figure 4-1: TV-PAL carriers after the proposed down conversion

After down conversion of the TV-PAL signal at RFE sensing receiver, the carrier frequencies at the input of spectrum sensing are: 1.75 MHz for picture carrier f_{pc}, 6.18 MHz for the suppressed color subcarrier f_{cs}, and 7.75 MHz for audio carrier $f_{ac.}$ Using these values in section 3.7.1.4 the exact cyclostationary features resulting from the carrier frequencies can be found. The carrier frequencies and their cyclostationary features are shown in Table 4-1.

Table 4-1: SCF peaks locations of the primary signals

TV-PAL signal		
Carrier	**Spectral frequency** $\boldsymbol{f}$	**Cyclic frequency** $\boldsymbol{\alpha}$
f_{pc} (4 peaks)	±1.75 MHz	0
	0	±3.5 MHz
f_{ac} (4 peaks)	±7.75 MHz	0
	0	±15.5 MHz
f_{cs}	Color subcarrier is Suppressed	
(f_{pc}+ f_{ac}) term (4 peaks)	±3 MHz	±9.5 MHz
(f_{pc} - f_{ac}) term (4 peaks)	±4.75 MHz	±6 MHz
Wireless microphone signal		
f_c (4 peaks)	$\pm f_c$	0
	0	$\pm 2f_c$

The information relating to these cyclostationary features will be used in the following sections to develop spectrum sensing algorithms for TV-PAL and wireless microphone signals. Because these two signals have distinctive locations of SCF peaks, a simple classification approach is also developed.

4.3 Spectrum Sensing Algorithm for Wireless Microphone

Since there is no a-prior knowledge of the carrier frequency of wireless microphone signal within the 8 MHz channel, this proposed algorithm searches for the maximum cyclostationary peak at $f = 0$ axis and then compares it with the threshold. The flow chart of this algorithm is shown in Figure 4-2. After down conversion and sampling the received signal, the spectral correlation function of the signal is computed to obtain the cyclostationary features. The test statistics (*TS*) is given by:

$$TS = Max\ of\ \{S_y^{\alpha}(0)\}\,, \qquad \alpha \neq 0 \tag{4.1}$$

Suitable threshold is selected to obtain a fixed probability of false alarm of 10% as specified in WRAN standard. To find the threshold value, the cumulative distribution function (CDF) $F(x)$ of test statistics of AWGN is found using its histogram. From the so obtained CDF, the threshold value λ is obtained where $F(\lambda) = 0.9$.

If the test statistics of the received signal is greater than the threshold λ, this means the wireless microphone signal exists in the band under sensing. In this case, other TV bands are examined or sensing is performed again for the same band after certain time *T*, that depends on spectrum availability in the geographic area in which WRAN system is deployed. If the test statistic is less than the threshold, the band can be used by WRAN CR users.

4.4 Spectrum Sensing Algorithm for TV-PAL

This algorithm makes use of most of the cyclostationary features present in the TV-PAL signal. It is by averaging the cyclostationary features at spectral frequency $f = 0$ axis which has four peaks at $\alpha = \pm 3.5$ MHz and $\alpha = \pm 15.5$ MHz. The flow chart of this algorithm is shown in Figure 4-3. The test statistics is applied after down conversion and sampling and is given by:

$$TS = \frac{S_y^{-15.5}(0)+S_y^{-3.5}(0)+S_y^{+3.5}(0)+S_y^{+15.5}(0)}{4} \quad (4\text{-}2)$$

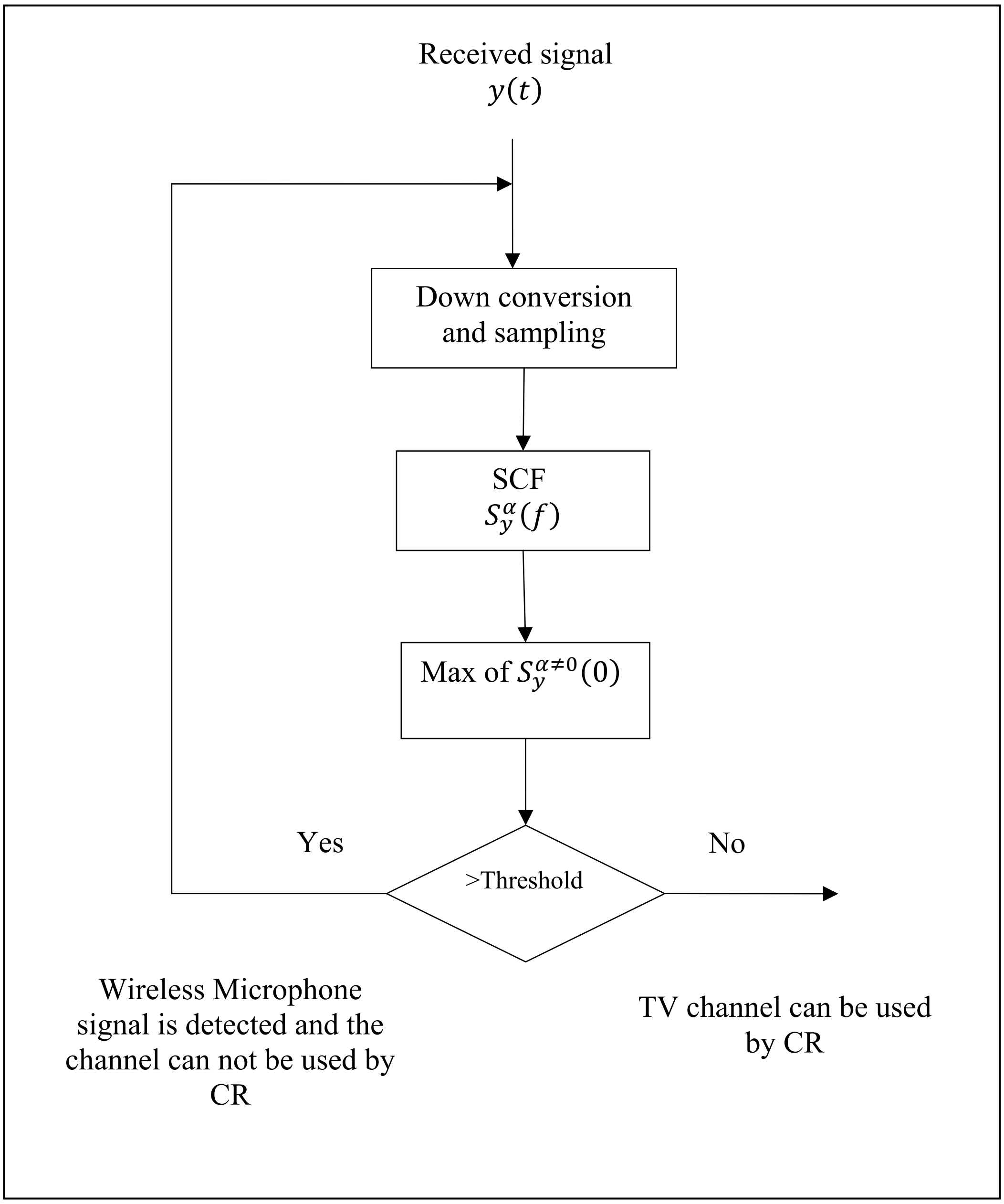

Figure 4-2: Flow chart of wireless microphone spectrum sensing algorithm

The threshold is selected in the same manner used for wireless microphone sensing algorithm to obtain a fixed probability of false alarm of 10%. Whereas test statistics in Eq. (4-2) is applied to AWGN and then the threshold, λ, is determined by CDF where $F(\lambda) = 0.9$. If the test statistic of the received signal is greater than the threshold λ, this means the TV-PAL signal exists in the band under sensing. In this case, we examine other TV bands or do sensing again of the same band after certain time *T*, that is derived from the study of spectrum availability in the given geographic area in which WRAN system is deployed. If the test statistic is less than the threshold, the band can be used by WRAN CR users.

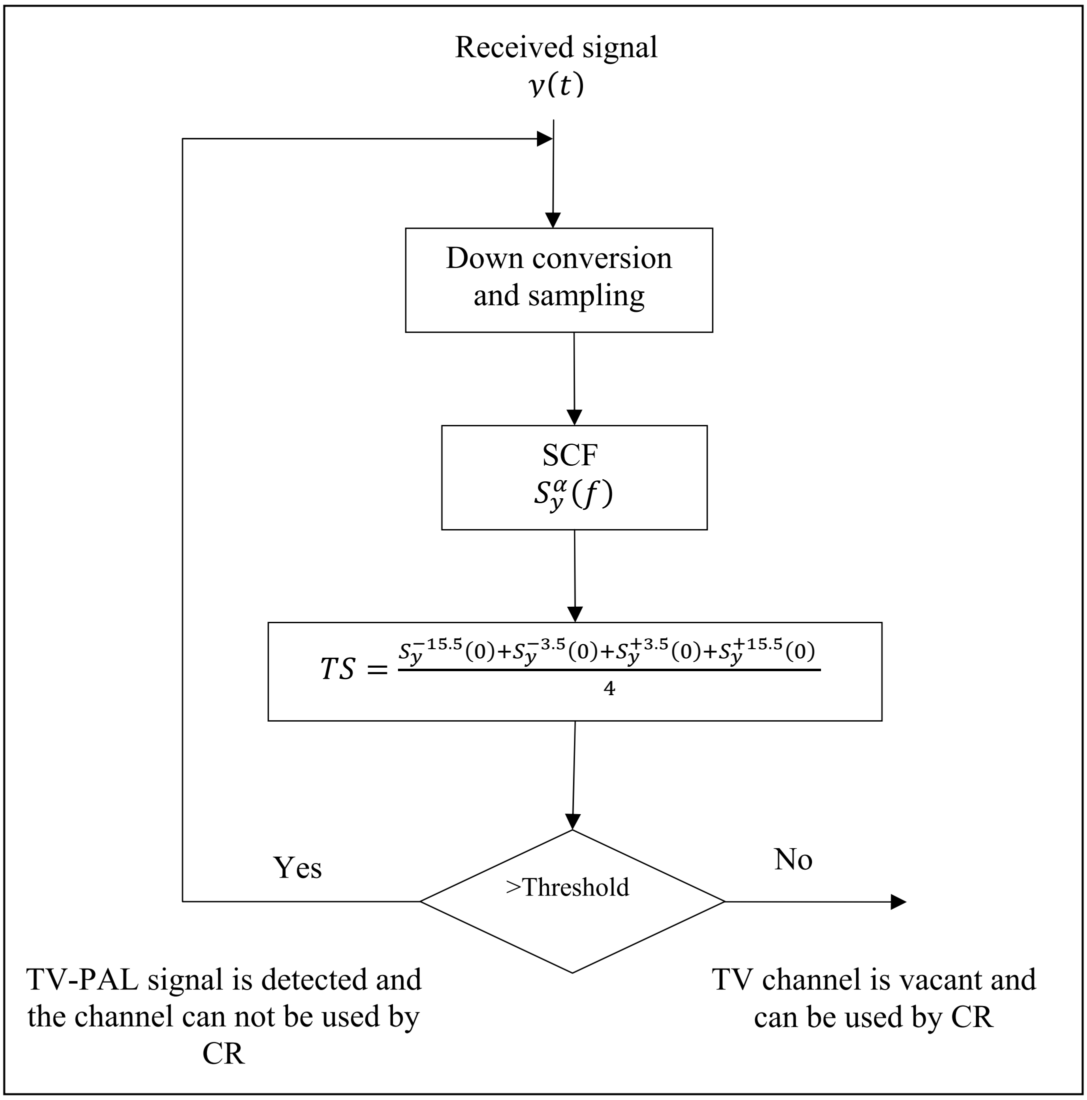

Figure 4-3: Flow chart of TV-PAL spectrum sensing algorithm

4.5 Primary Signals Classification Approach

In CR co-existence framework, there are multiple primary systems operating in same frequency bands and in the same area. In such environment and in order to support adaptability of the CR users, classification of primary signals is required. Having the knowledge of which PU is operating, SUs can adapt their parameters to provide the required protection for that primary system. Classification is also important in spectrum management function in CR. For example, if the identified primary signal has a bandwidth less than other primary signals, CR can optimize the use of the spectrum band by suitably utilizing the fractions of the frequency band available for use. This feature is called bandwidth scalability and can be used to improve spectrum utilization [63].

In the case of WRAN CR, we need to classify and identify TV-PAL and wireless microphone signals. Wireless microphone occupies only 200 kHz of 8 MHz TV channel and the rest of the channel can be utilized by CR without causing harmful interference to wireless microphone receiver. Without distinction of wireless microphone from TV-PAL, WRAN CR can not make good use of bandwidth scalability by using the available fractions of TV channel.

The proposed classification approach to distinguish between TV-PAL and wireless microphone is based on the difference between the cyclostationary features of these two signals. This difference results from the fact that TV-PAL has two carriers; picture carrier f_{pc} and audio carrier f_{ac} as in Eq. (3.21) while wireless microphone signal has one carrier f_c as in Eq. (3.22). As discussed in section 3.7.1.4, TV-PAL has additional peaks as its cyclostationary features at the following locations in term of (f, α): $\left(\pm \frac{f_{pc} \pm f_{ac}}{2}, \pm\left(f_{pc} \mp f_{ac}\right)\right)$. The Locations of these peaks after down conversion of the TV-PAL signal are shown in Table (4-1) which are $(\pm 4.75\ MHz, \pm 6\ MHz)$ and $(\pm 3\ MHz, \pm 9.5\ MHz)$. Figure 4-4 shows the flow chart of the proposed approach. As before, the received signal is down converted and sampled in the RFE of the sensing receiver. Then, the SCF is computed.

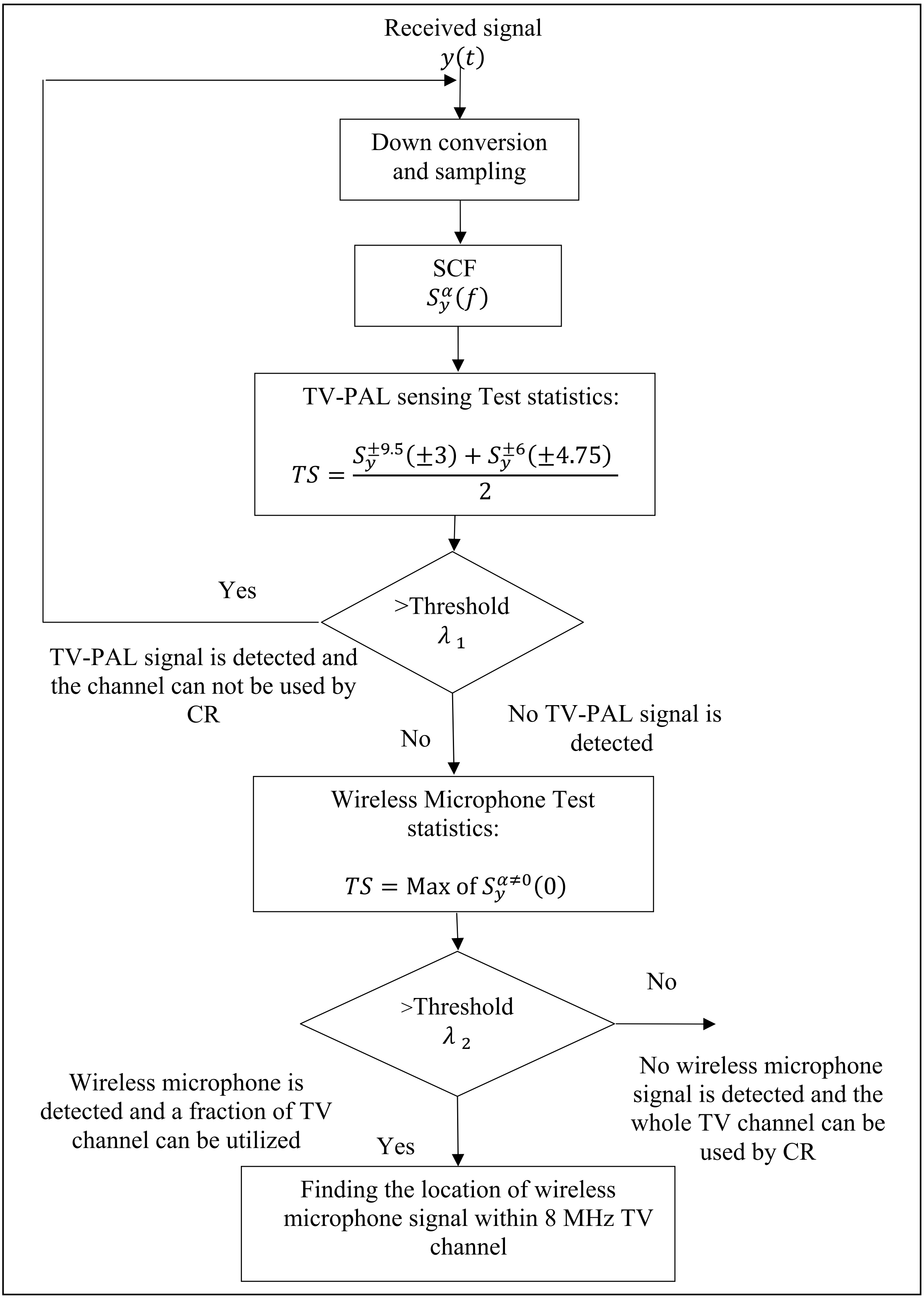

Figure 4-4: Flow chart of classification approach for spectrum sensing

The first test statistics is used for identifying PAL signal by averaging the magnitude of the peaks at the mentioned locations. If the average is greater than the threshold λ_1, this means PAL signal occupies the channel and spectrum sensing will be repeated on other channels. The second test statistics is for wireless microphone signal by comparing the maximum peak at $f = 0$ axis with the threshold λ_2. The maximum peak is used because PAL signal identification is not considered in this test statistics and the exact carrier frequency f_c is not known. The case when the test statistics is greater than λ_2 identifies the presence of wireless microphone which occupies only 200 kHz of 8 MHz TV channel, hence the rest of the channel can be used by CRs under the condition of not causing harmful interference to wireless microphone system. To locate the bandwidth used by wireless microphone, the carrier frequency is determined by finding the location of detected maximum peak at $f = 0$ axis. When the test statistics is less than λ_2 the whole channel can be utilized by CR.

This approach incorporates primary signals classification and sensing in one simple algorithm. By using cyclostationarity for classification, we benefit from its robustness against noise uncertainty. This approach makes the advantage of using the theory of cyclostationarity for CR over energy detector more obvious. It can be recalled that an energy detector simply provides a measure of energy of the received signal and does not differentiate between noise and primary signals, nor between one primary signal and the other.

4.6 Methodology

As introduced in Chapter 1, for the assessment of the proposed algorithms; these performance factors are considered:

- Probability of detection (P_d) and probability of classification (P_c).
- Probability of false alarm (P_{fa}).
- Signal-to-noise ratio (SNR).
- Sensing time (t_s).

- Noise uncertainty.
- AWGN and fading channels.

For sensing algorithms, the performance is evaluated by computing P_d vs. SNR and it is compared with that of an energy detector for fixed P_{fa} and t_s. Similarly, for classification algorithm, the performance is evaluated in terms of P_c vs. SNR. Figure 4-5 shows the flow chart of the methodology.

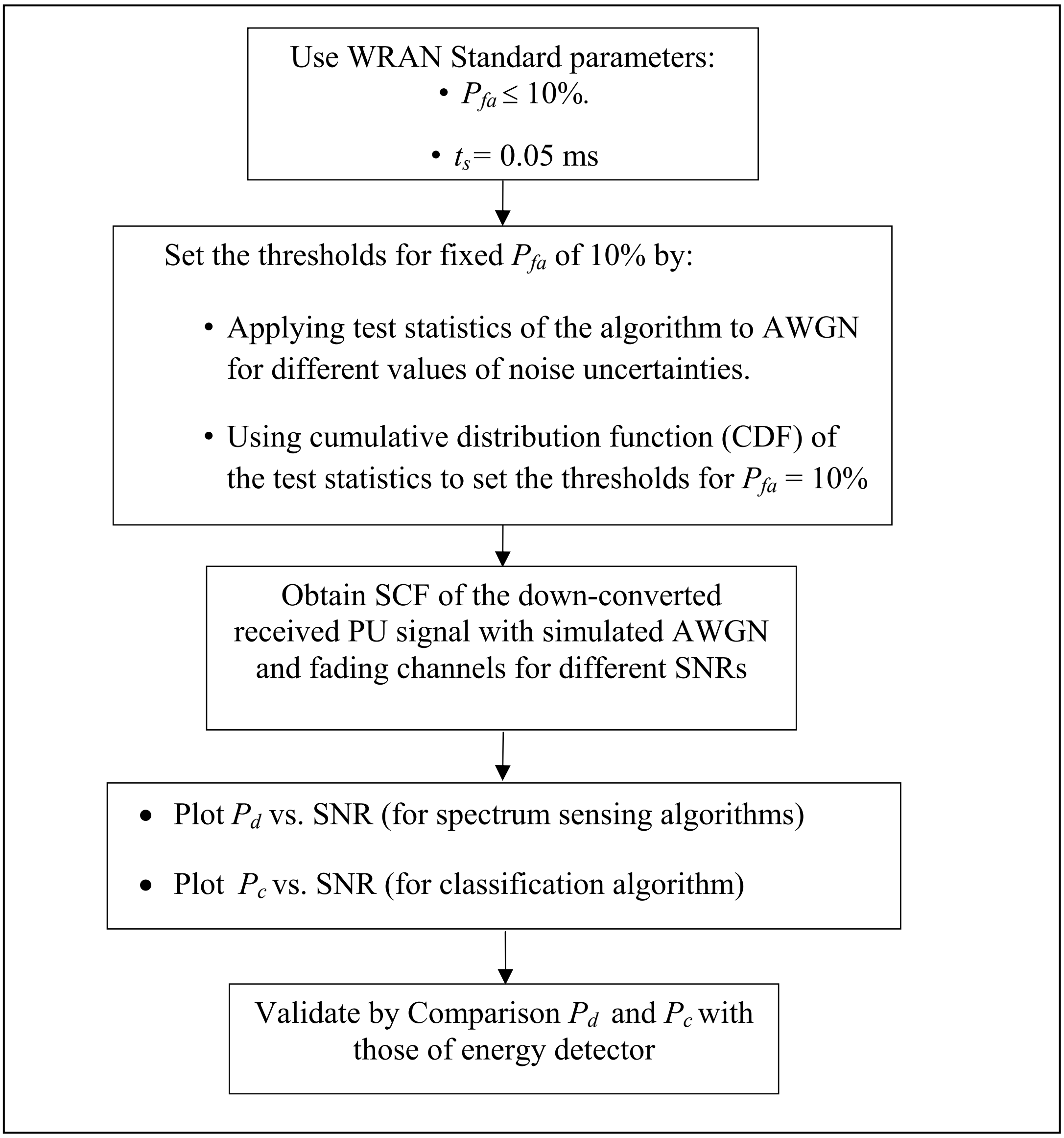

Figure 4-5: Methodology

In computing P_d, using cyclostationary features detector, the appropriate sensing time (t_s), P_{fa} and SNRs range are used and the result is compared with that of energy detector. To determine the thresholds for fixed P_{fa}, CDF of test statistics of AWGN is used. Before calculating SCF, the received signal is down-converted to 0-8 MHz. The sensitivity of the proposed algorithms and energy detector can be evaluated by plotting P_d against SNR for specific value of sensing time and noise uncertainty. In addition to AWGN channel, fading channel is also considered in the evaluation. For classification algorithm, P_c is used to evaluate the performance of the proposed classification approach by plotting P_c against SNR. As in sensing algorithms, the thresholds for classification algorithm are determined using CDF to obtain fixed P_{fa}.

The simulation parameters and fading channel profile are given in Chapter 5 along with the results obtained based on the methodology.

4.7 Summary

In this chapter, spectrum sensing algorithms for TV-PAL and wireless microphone are proposed based on cyclostationary features obtained in Chapter 3. The cyclostationary features of down-converted signal are stated first to locate the exact positions of the peaks in SCF. In addition to spectrum sensing, the classification approach for primary signal is also proposed to support CR adaptability and scalability. This approach is based on the distinctive cyclostationary features of TV-PAL and wireless microphone to help identify which primary signal is operating in the TV channel. Finally, the methodology to assess the performance of the proposed algorithms is stated. The performance of the proposed algorithms is analyzed and discussed next in Chapter 5.

CHAPTER 5

RESULTS & DISCUSSION

5.1 Introduction

In this chapter, the algorithms proposed in previous chapter are evaluated over AWGN and fading channels under noise uncertainty. First, the power spectrum and spectral correlation function of the simulated PUs signals are shown. Then, the performance of spectrum sensing algorithms based on cyclostationary feature for wireless microphone and TV-PAL are evaluated in comparison with that of energy detector. The classification approach is also evaluated using probability of correct classification.

5.2 Power Spectrum of Simulated Primary Signals

The TV-PAL and wireless microphone signals in Eq. (3.21) and Eq. (3.22), respectively are simulated using MATLAB®. Table 5-1 shows the parameters for the simulation.

Table 5-1: Primary signals simulation parameters

Parameters	Value
Channel bandwidth	8 MHz
Wireless microphone signal bandwidth	200 kHz
Sampling frequency	16 MHz
f_{pc}	1.75 MHz
f_{ac}	7.75 MHz
PAL FM modulation frequency deviation	50 kHz
f_c	2 MHz
Wireless microphone FM frequency deviation	15 kHz

Power spectrums of the generated wireless microphone and TV-PAL are shown in Figure 5-1 and Figure 5-2, respectively.

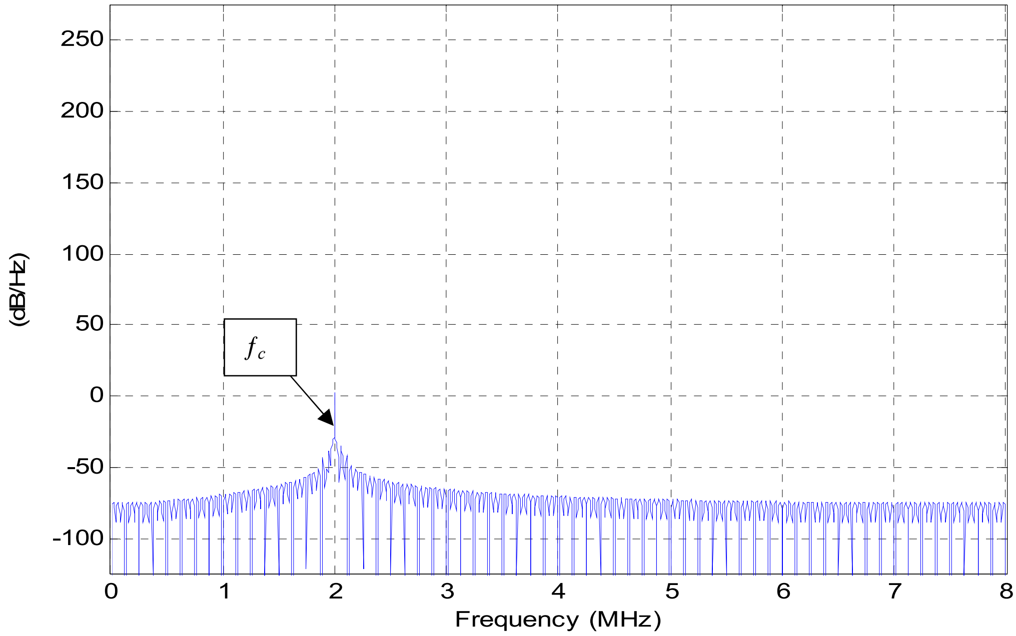

Figure 5-1: Power spectrum of wireless microphone signal

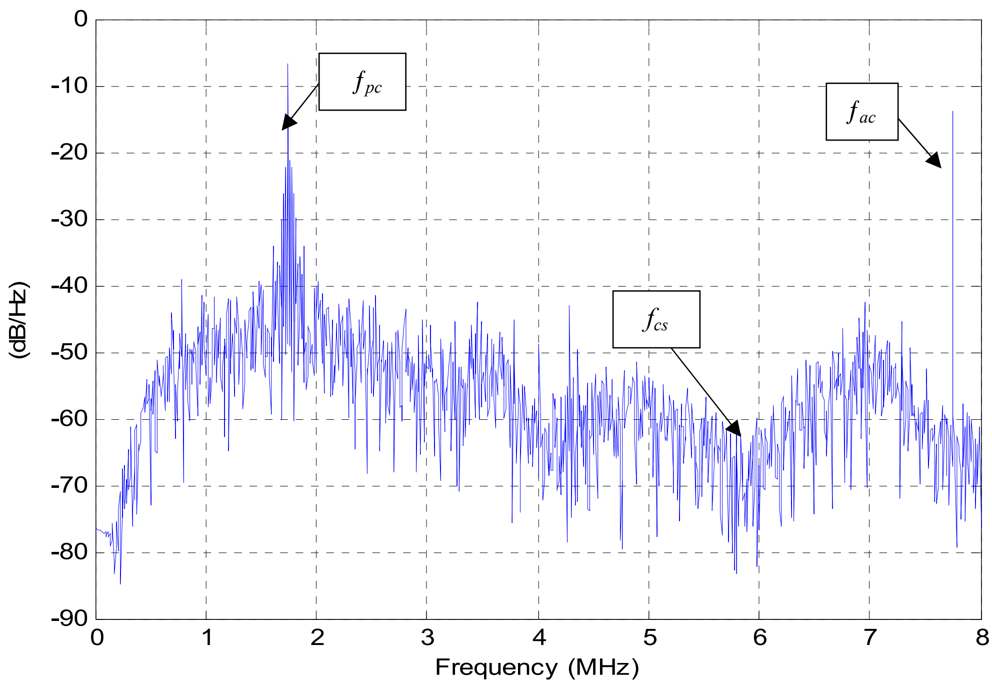

Figure 5-2: Power spectrum of TV-PAL signal

Power spectrum is a special case of SCF when $\alpha = 0$ (Eq.(3.20)) where AWGN has flat contribution. Figure 5-3 shows power spectrum of AWGN in 8 MHz TV channel.

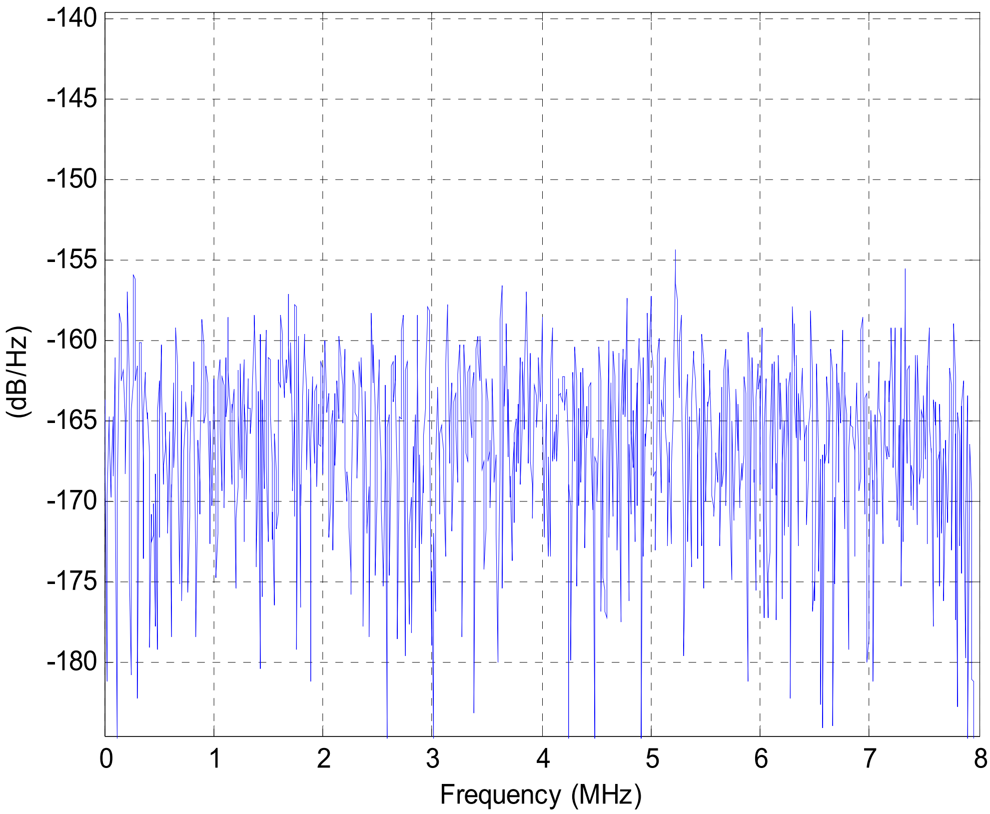

Figure 5-3: Power spectrum of AWGN

5.3 Spectral Correlation Function of Primary Signals

Based on Eq. (3.18) and Eq. (3.19), MATLAB® simulation is used to obtain cyclostationary features of the simulated primary signals. Figure 5-4 and Figure 5-5 show those features for wireless microphone and TV-PAL signals, respectively. As discussed in Chapter 3 and using the parameters in Table 5-1, Figure 5-4 shows that SCF of wireless microphone signal has four peaks at these locations in term of $(f\ MHz, \alpha\ MHz)$: $(\pm 2{,}0)$ and $(0, \pm 4)$ and Figure 5-5 shows that SCF of TV-PAL has sixteen peaks at: $(\pm 1.75, 0)$, $(\pm 7.75, 0)$, $(0, \pm 3.5)$, $(0, \pm 15.5)$, $(\pm 3, \pm 9.5)$ and $(\pm 4.75, \pm 6)$. These are the same features calculated in Table 4-1.

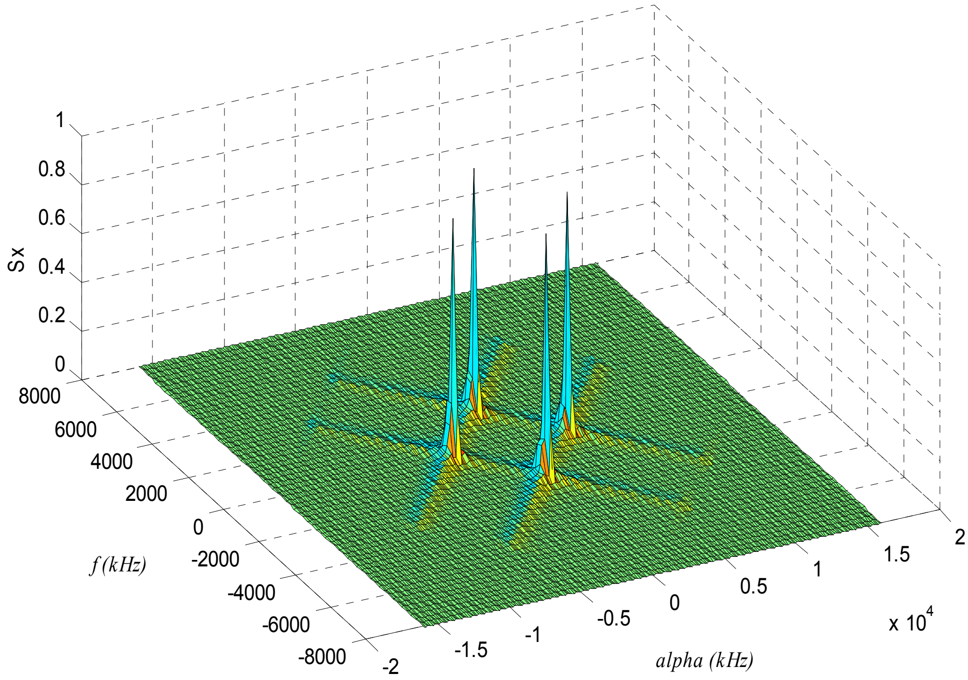

Figure 5-4: SCF of wireless microphone signal

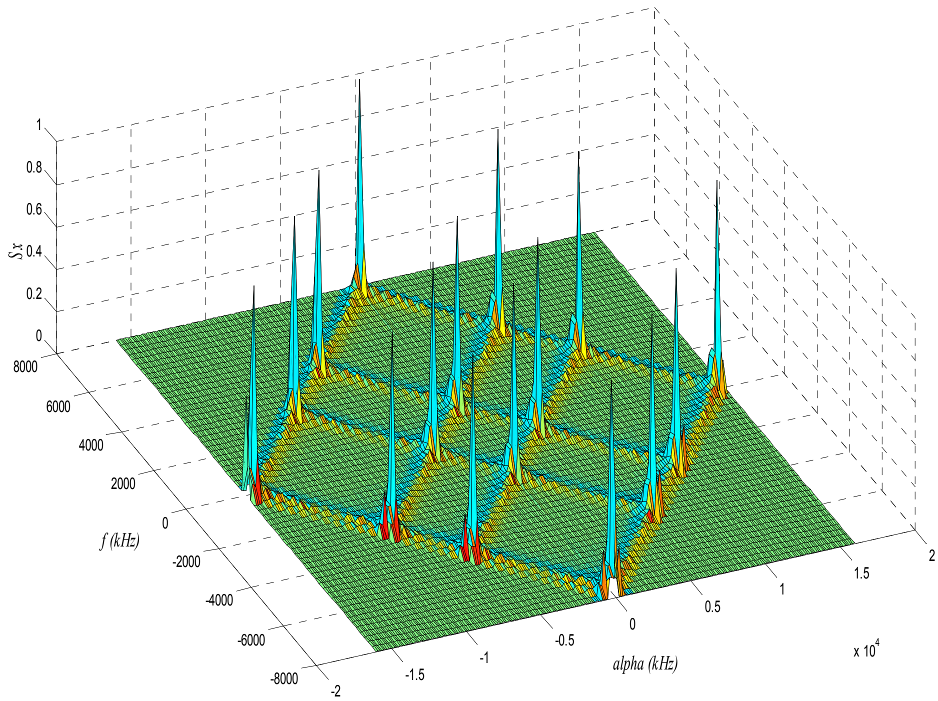

Figure 5-5: SCF of TV-PAL signal

Figure 5-6 and Figure 5-7 show the contour graphs of SCFs in Figure 5-4 and Figure 5-5. The contour graphs show the peaks locations of SCF in two-dimensional representation of a surface graph. These graphs type is analogous to maps showing elevation. Note that all figures are normalized using the maximum peaks of SCF.

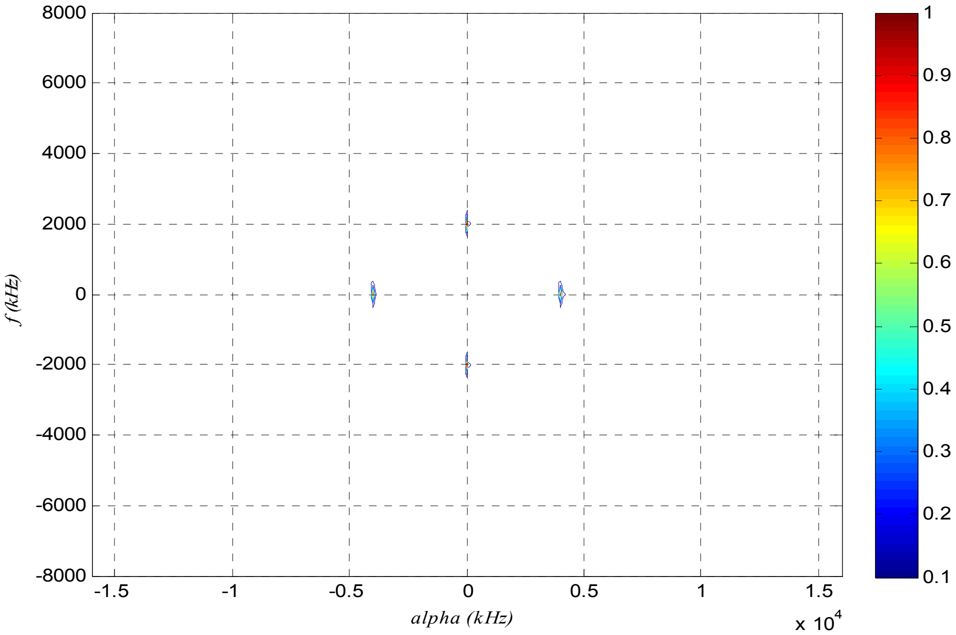

Figure 5-6: Contour graph of SCF of wireless microphone signal

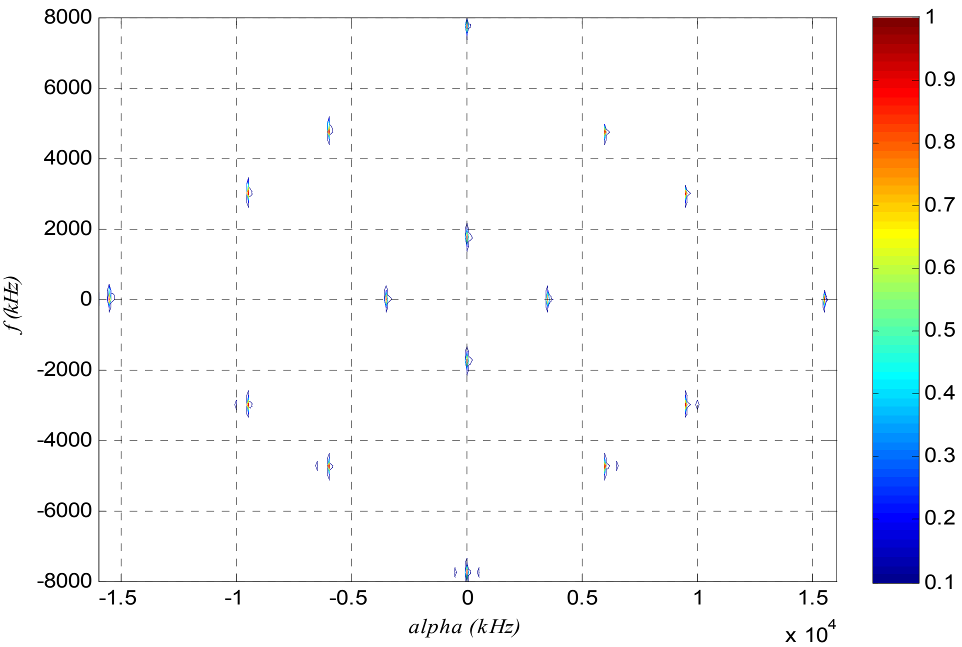

Figure 5-7: Contour graph of SCF of TV-PAL

SCF of AWGN is shown in Figure 5-7. As discussed in chapter 3, AWGN ideally has no cyclostationary features (i.e. $S_w^{\alpha}(f) = 0$ when $\alpha \neq 0$) and only has flat PSD.

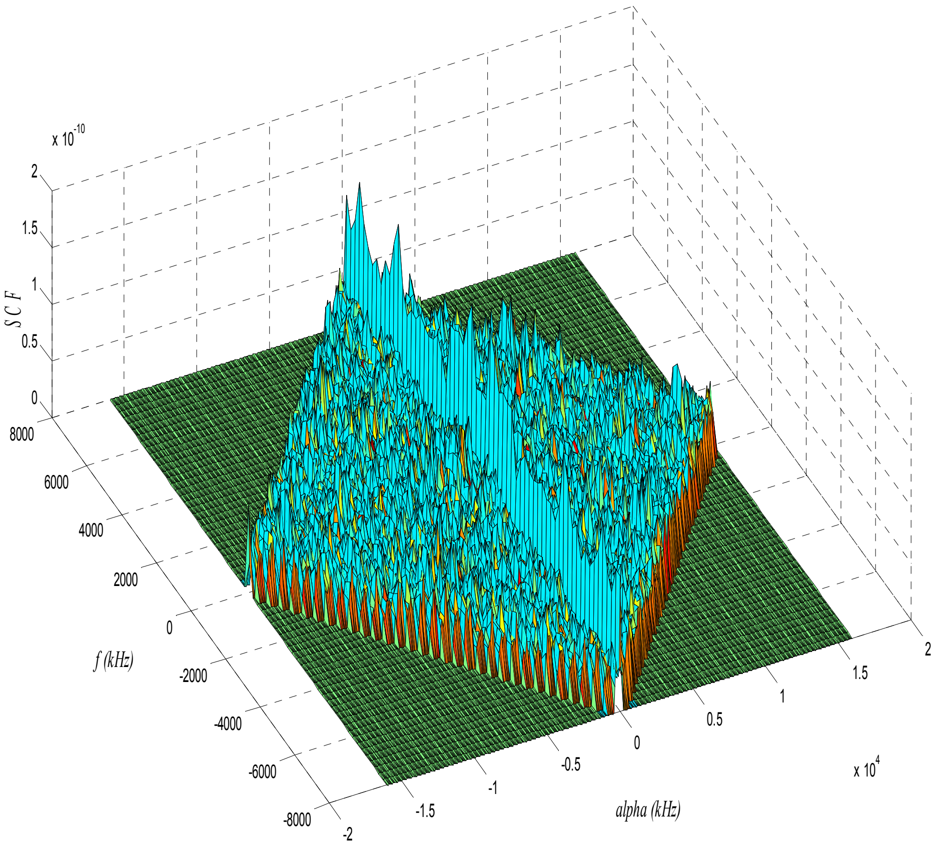

Figure 5-8: SCF of AWGN

5.4 Results of the Proposed Cyclostationarity-Based Spectrum Sensing

Performance Parameter – Probability of Detection: To evaluate the performance of the proposed spectrum sensing algorithms, probability of detection is used as performance parameter. The probability of detection performance of an energy detector is used as a bench mark to compare and evaluate the performance of the proposed techniques.

System Assumptions: The comparison is done under a fixed probability of false alarm (P_{fa}) and sensing time (t_s). $P_{fa} = 0.1$ and $t_s = 0.05\, ms$ are used in this comparison and two types of channel are considered AWGN and multipath fading channel.

Deriving the thresholds: In the proposed cyclostationary features-based spectrum sensing algorithms the values of the thresholds (λ) are set for $P_{fa} = 0.1$. As discussed in chapter 4, cumulative distribution function (CDF) of test statistics when input signal $y(t)$ is only AWGN is used to set the threshold, λ. Figure 5-9 and Figure 5-10 show the thresholds for wireless microphone and TV-PAL sensing algorithms for 0, 1 and 2 dB noise uncertainty. The values of the thresholds are indicated circular dots when CDF=0.9.

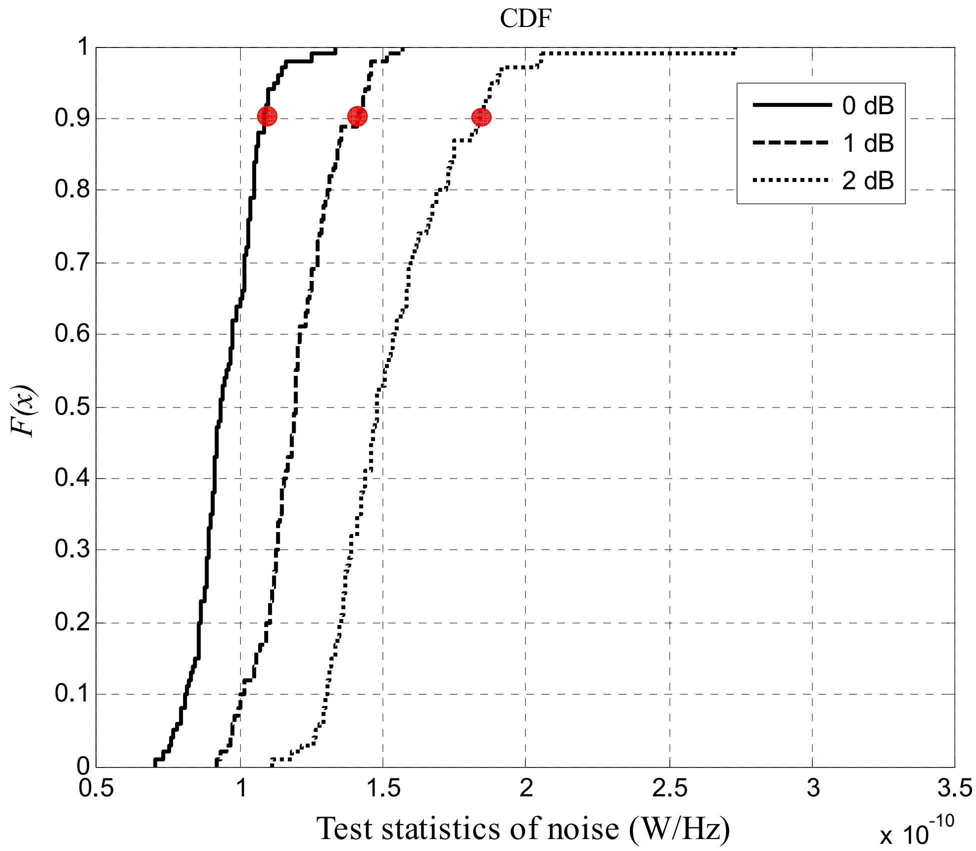

Figure 5-9: Determining the thresholds for wireless microphone sensing algorithm for 0, 1 and 2 dB noise uncertainties

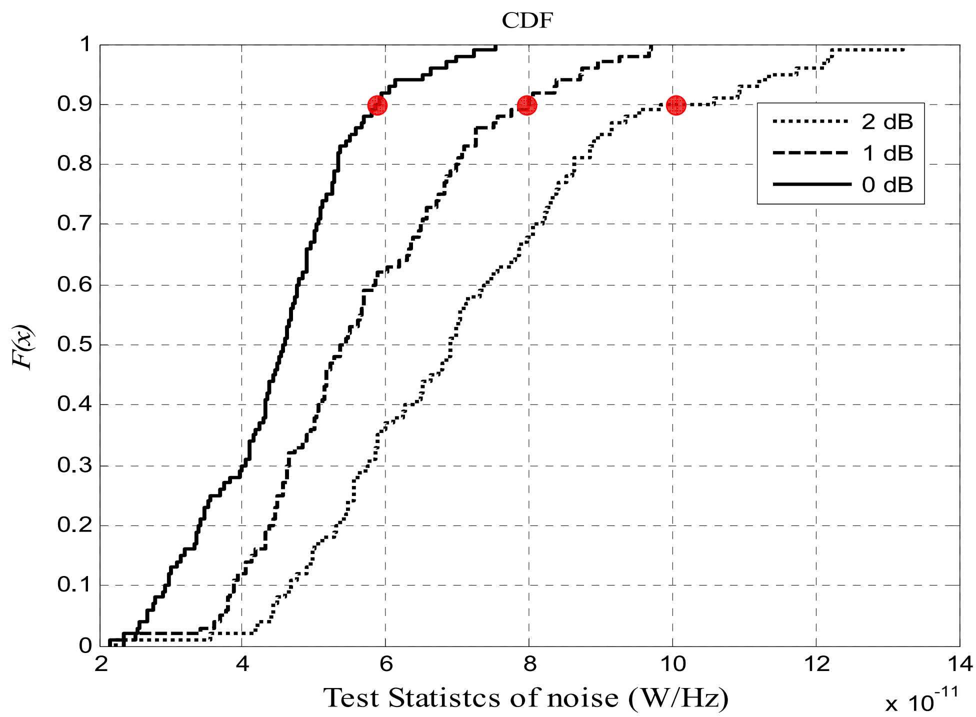

Figure 5-10: Determining the thresholds for TV-PAL sensing algorithm for 0, 1 and 2 dB noise uncertainties

5.4.1 Performance of Proposed Wireless Microphone Sensing Algorithm

In addition to simulation parameters in Table 5-1, noise floor of -94 dBm is used in this evaluation (calculated in chapter 3). The performance of the proposed algorithm is evaluated over AWGN and multipath fading channels under noise uncertainty scenario. Robust statistics discussed in section 3.3.3 is used to model noise uncertainty. Figures 5-11, to 5-16 show the performance over AWGN and fading channel in comparison with energy detector in the cases of 0, 1 and 2 dB noise uncertainties.

a) Results in AWGN

It can be seen from Figure 5-11, the proposed cyclostationarity-based spectrum sensing for wireless microphone achieves probability of detection (P_d) of 90% at SNR of -12 dB, while energy detector achieves this value of P_d at -8 dB SNR. Hence, in the case of no noise uncertainty the proposed algorithm performs better by 4 dB SNR.

This means that using cyclostationary features detector is more sensitive for detection of wireless microphone signal than energy detector by 4 dB SNR. For 100% P_d, the proposed algorithm requires -11 dB SNR, while energy detector requires -6 dB SNR which makes the proposed algorithm better by 5 dB.

Figure 5-12 shows that, when noise uncertainty is 1 dB, the proposed algorithms achieves P_d of 90% at -11 dB SNR, while energy detector achieves it at -2 dB. For P_d of 100%, the proposed algorithm achieves it at -10 dB SNR, while energy detector requires -1 dB to achieve this P_d. Hence, for 90% and 100% P_d the proposed algorithm outperforms energy detector by 9 dB SNR. This indicates that, for 1 dB noise uncertainty, the performance of the proposed algorithm degrades by nearly 1 dB, while energy degrades by 6 dB and 5 dB for 90% and 100% P_d; respectively. For the case of 2 dB noise uncertainty, shown in Figure 5-13, the performance of energy detector degrades by about 2.8 dB SNR for the achievement of 90% P_d and by 2 dB for 100%. On the other hand, the performance of the proposed algorithm degrades only by 1 dB.

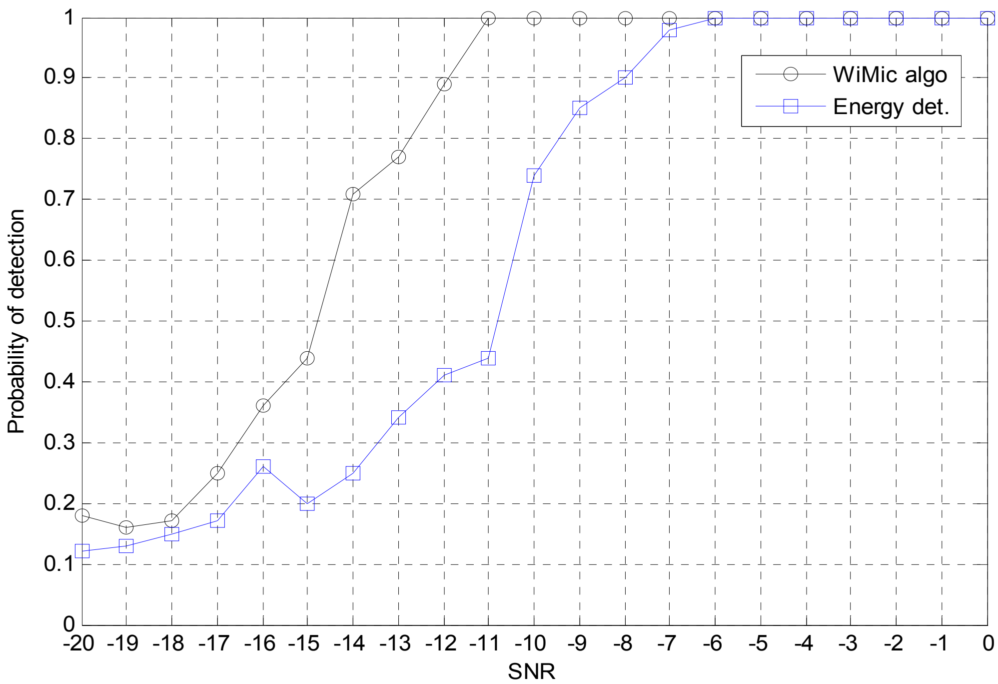

Figure 5-11: The performance of the proposed wireless microphone sensing algorithm vs. energy detector in the case of AWGN channel and 0 dB noise uncertainty

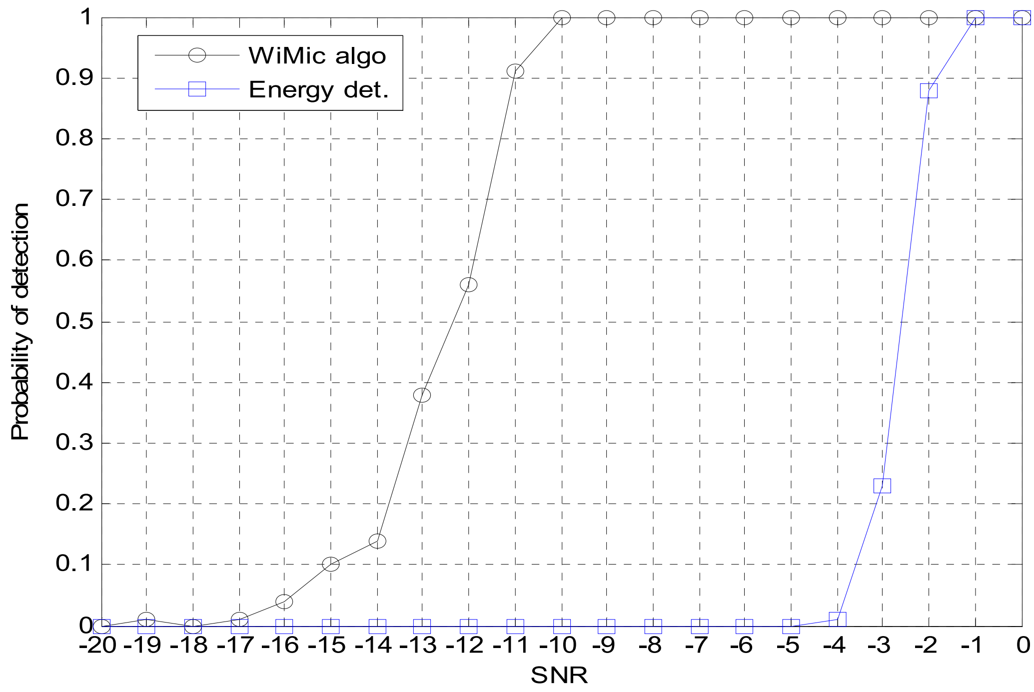

Figure 5-12: The performance of the proposed wireless microphone sensing algorithm vs. energy detector over AWGN channel and 1 dB noise uncertainty

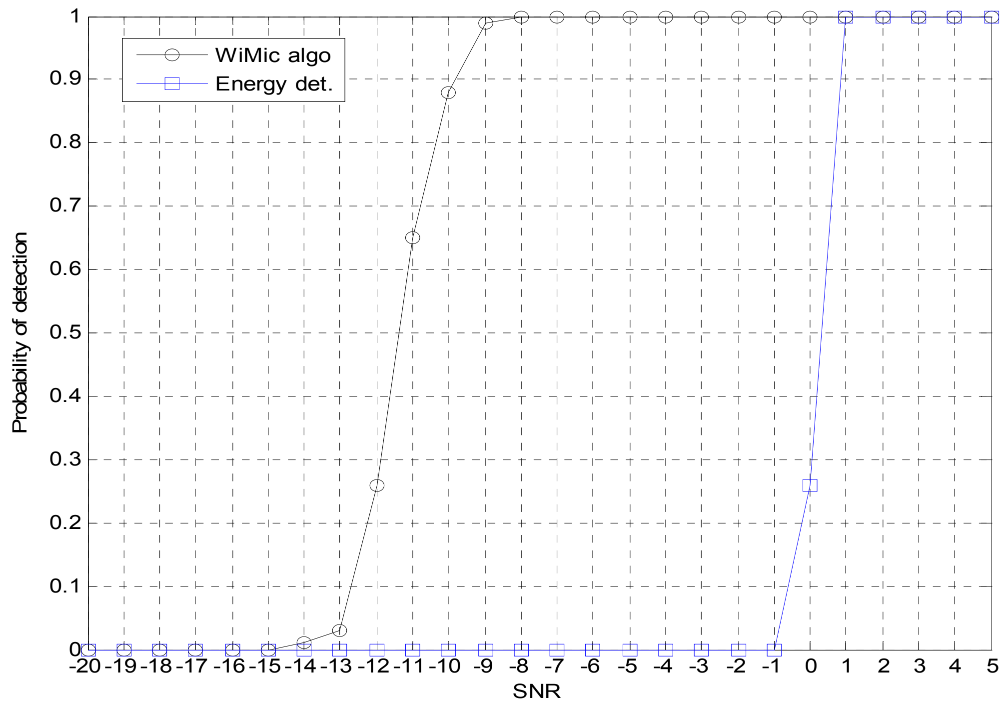

Figure 5-13: The performance of the proposed wireless microphone sensing algorithm vs. energy detector in the case of AWGN channel and 2 dB noise uncertainty

From these results and discussion, the performance of the proposed algorithm is obviously better in all cases of noise uncertainty. In addition, its performance is less susceptible to the changes in noise floor than those in energy detector whose performance degrades by 6 dB at noise uncertainty of 1 dB.

a) Results in Multipath Fading Channel

To evaluate the performance of the proposed wireless microphone sensing algorithm in both AWGN and multipath fading channel, the fading channel profile shown in Table 5-2 is recommended by [64] to test the proposed algorithms for WRAN CRs systems. The profile includes six paths and the associated delays and amplitude relative to first path as well as the Doppler frequencies.

Table 5-2: Multipath fading channel profile for evaluation of 802.22 WRAN

Profile	Path 1	Path 2	Path 3	Path 4	Path 5	Path 6
Excess delay	0	3 µsec	8 µsec	11 µsec	13 µsec	21 µsec
Relative amplitude	0	-7 dB	-15 dB	-22 dB	-24 dB	-19 dB
Doppler frequency	0	0.10 Hz	2.5 Hz	0.13 Hz	0.17 Hz	0.37 Hz

Figures 5-14 to 5-16 show performance of the proposed wireless microphone spectrum sensing algorithm and that using energy detector over the simulated Rayleigh multipath fading channel with 0, 1, and 2 dB noise uncertainties, respectively.

It can be seen that, in this channel condition, the performance of the proposed algorithm is still superior to energy detector. While energy detector degrades significantly in the case of noise uncertainty, the proposed algorithm is less affected by noise uncertainty. For 0 dB uncertainty in Figure 5-14, the proposed algorithm outperforms energy detector by 3 dB for achievement of 100 % P_d . When noise uncertainty becomes 1 dB as depicted in Figure 5-15, the proposed algorithm performs better by 8 dB. The gain in the performance by using the proposed algorithm increases to 10 dB in the case of 2 dB noise uncertainty as shown in Figure 5-16.

The superior performance of the proposed algorithm over AWGN and multipath fading channel is attributed to that noise has no cyclostationary features at $\alpha \neq 0$ – an attribute that is the motivation in using cyclostationary features for spectrum sensing in CR. On the other hand, according to Parseval's theorem, energy detection is equivalent to integration of PSD of the signal over its bandwidth. However, the noise which has a flat PSD over the signal's bandwidth also contributes a fixed amount to the detected energy. Hence, noise uncertainty affects the performance of energy detector significantly.

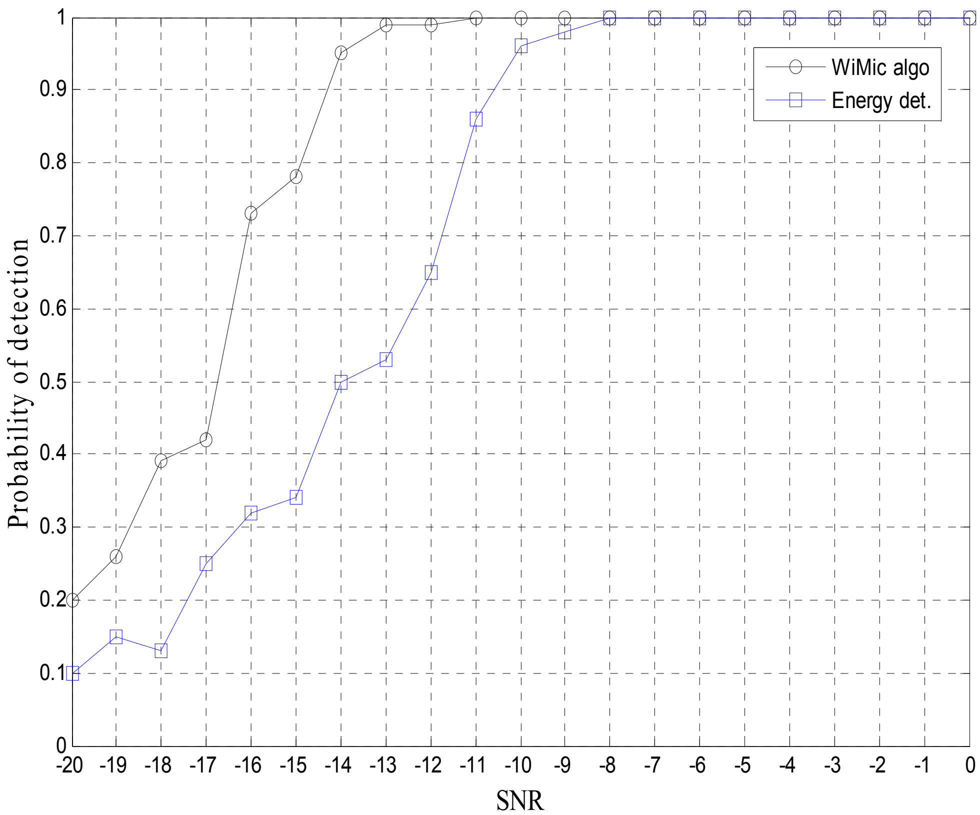

Figure 5-14: The performance of the proposed wireless microphone sensing algorithm vs. energy detector over Rayleigh channel and 0 dB noise uncertainty

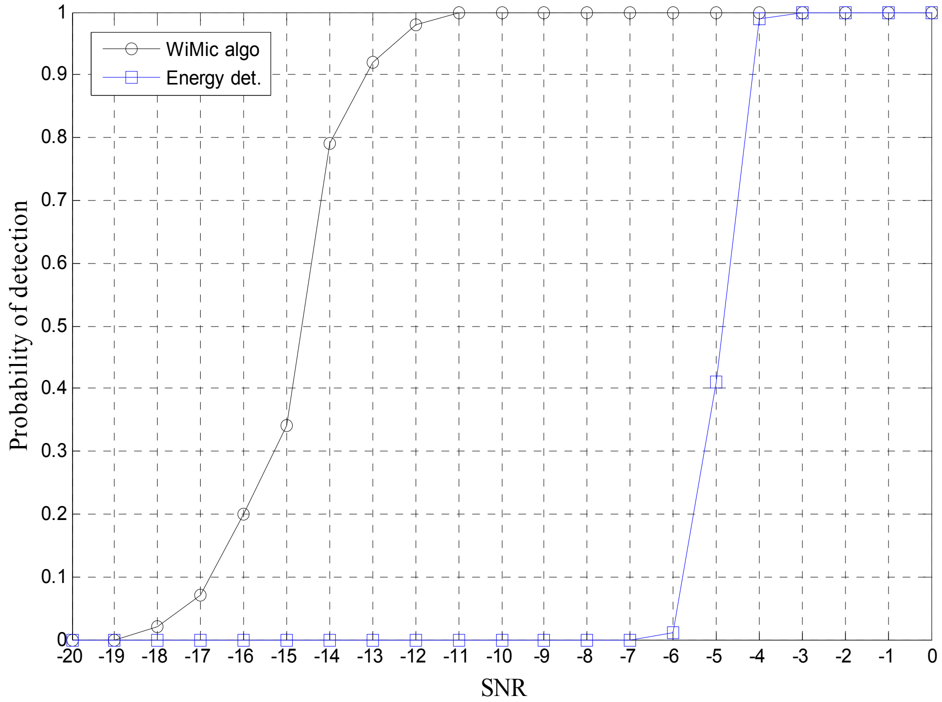

Figure 5-15: The performance of the proposed wireless microphone sensing algorithm vs. energy detector over Rayleigh channel and 1 dB noise uncertainty

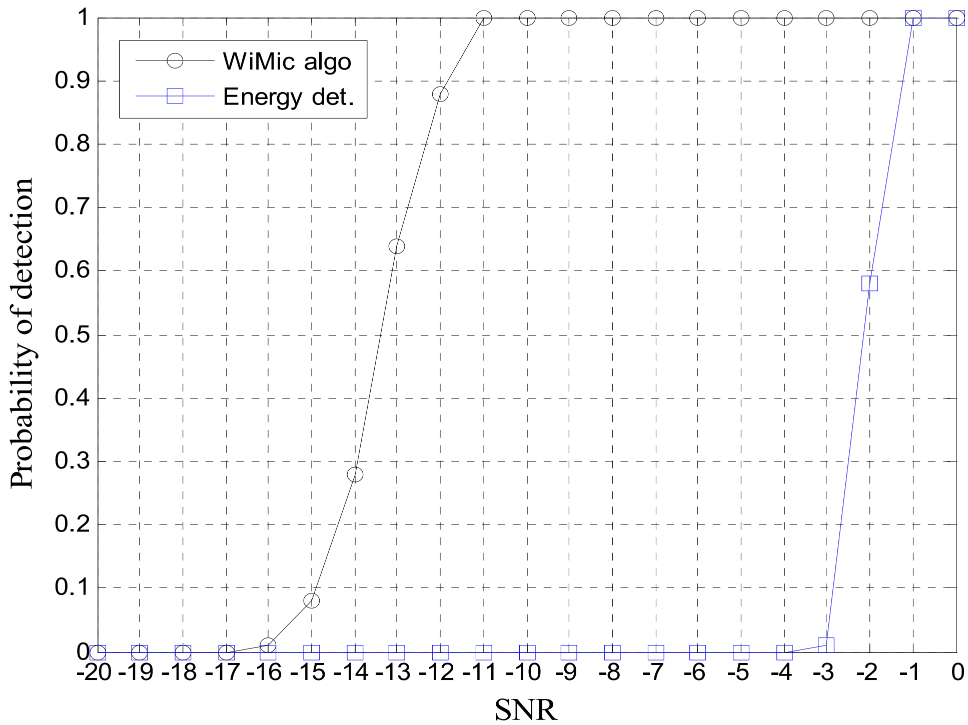

Figure 5-16: The performance of the proposed wireless microphone sensing algorithm vs. energy detector over Rayleigh channel and 2 dB noise uncertainty

5.4.2 Performance of Proposed TV-PAL Sensing Algorithm

In this performance evaluation, the same simulation parameters used earlier for wireless microphone sensing algorithm are considered here. The thresholds for this algorithm are shown in Figure 5-10. As in wireless microphone algorithm, first the evaluation is done over AWGN, which has a noise floor of -94 dBm, then over Rayleigh fading channel, shown in Table 5-3.

a) Results in AWGN

Figures 5-17 to 5-19 show the comparison between the proposed TV-PAL sensing algorithm and that of energy detector over AWGN. For 0 dB noise uncertainty in Figure 5-17, the proposed algorithm achieves 90 % P_d at -14 dB SNR, while energy detector achieves it at -9 dB. This makes the proposed algorithm better by 5 dB. For 100% P_d, the proposed algorithm requires -12 dB SNR while energy detector requires -7 dB SNR. The performance of energy detector degrades significantly when noise uncertainty becomes 1 dB as depicted in Figure 5-18. It can be seen that while energy detector requires -2 dB SNR to achieve 90 % P_d, the proposed sensing algorithm requires only -12 dB SNR. To achieve 100 % P_d the proposed algorithm requires -10 dB SNR, while energy detector requires 9 dB more to achieve this P_d.

Figure 5-19 shows the evaluation for 2 dB noise uncertainty. In this case the proposed algorithm achieves 90 % P_d at about -10.3 dB SNR, while energy detector achieves it at about 0.8 dB SNR. For 100 % P_d the proposed algorithm requires -9 dB SNR and the energy detector requires 1 dB SNR.

b) Results in Multipath Fading Channel

For evaluation over multipath fading channel, the channel profile shown in Table 5-2 is used to model Rayleigh fading. Figures 5-20 to 5-22 show the performance comparison between energy detector and the proposed TV-PAL sensing algorithm over fading channel for 0, 1 and 2 dB noise uncertainties, respectively. It can be seen that the proposed sensing algorithm for TV-PAL signal performs well in multipath fading channel. In the case of 0 dB noise uncertainty shown in Figure 5-20, energy detector requires about -9.7 dB SNR to achieve P_d of 90 % and -8 dB SNR for P_d of 100%. The proposed algorithm requires -13 dB SNR to achieve 90 % P_d and -11 dB for 100 % P_d. For 1 dB noise uncertainty performance comparison shown in Figure 5-21, the performance of energy detector degrades significantly. While it requires about -2.5 dB SNR to achieve 90 % P_d, the proposed algorithm requires only SNR of about -10.7 dB to achieve the same P_d. For 100% P_d, the proposed algorithm outperforms energy detector by 7 dB, where it requires only -9 dB SNR while energy detector requires -2 dB SNR.

For 2 dB noise uncertainty shown in Figure 5-22, the proposed algorithm is able to achieve 90% P_d at about -9.5 dB SNR while energy detector requires about -0.2 dB to achieve it. To achieve 100 % P_d, the proposed algorithm requires -8 dB SNR less than energy detector which requires 0 dB SNR.

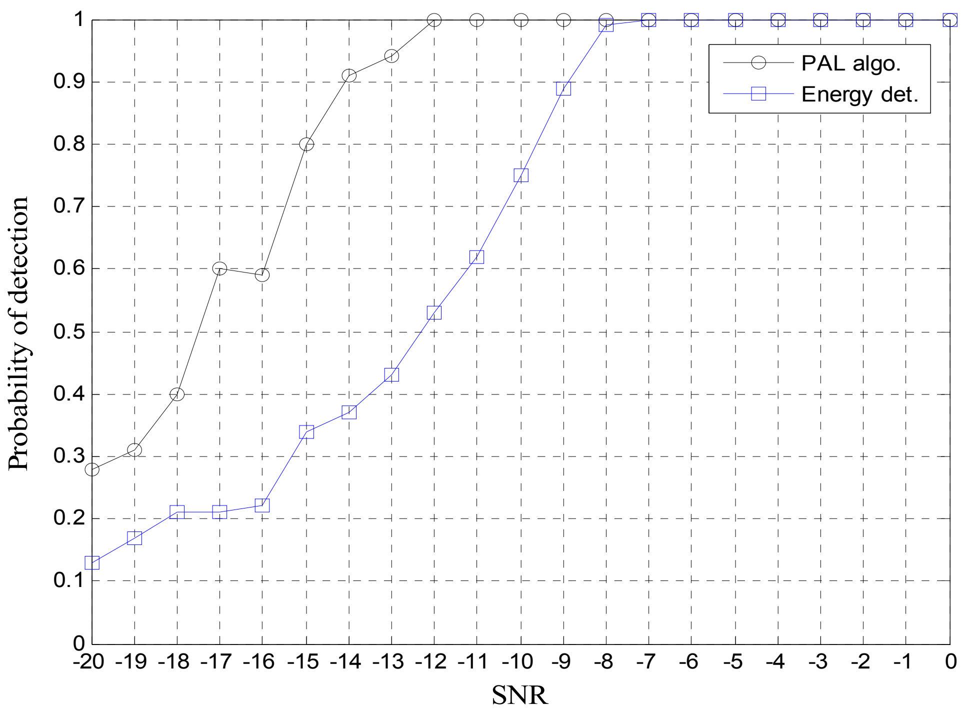

Figure 5-17: The performance of the proposed TV-PAL sensing algorithm vs. energy detector over AWGN channel and 0 dB noise uncertainty

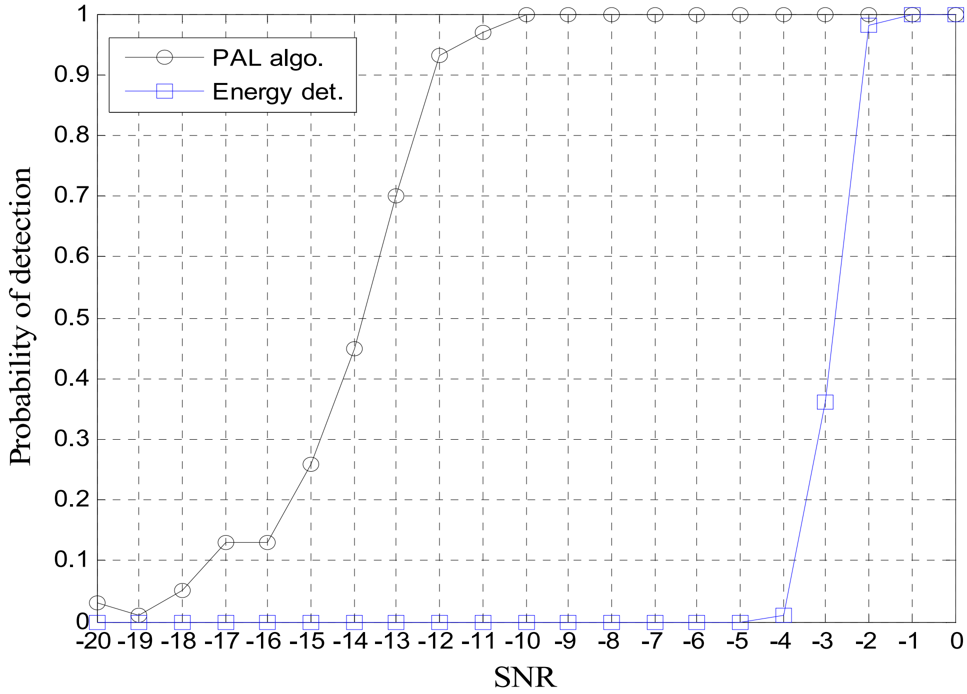

Figure 5-18: The performance of the proposed TV-PAL sensing algorithm vs. energy detector over AWGN channel and 1 dB noise uncertainty

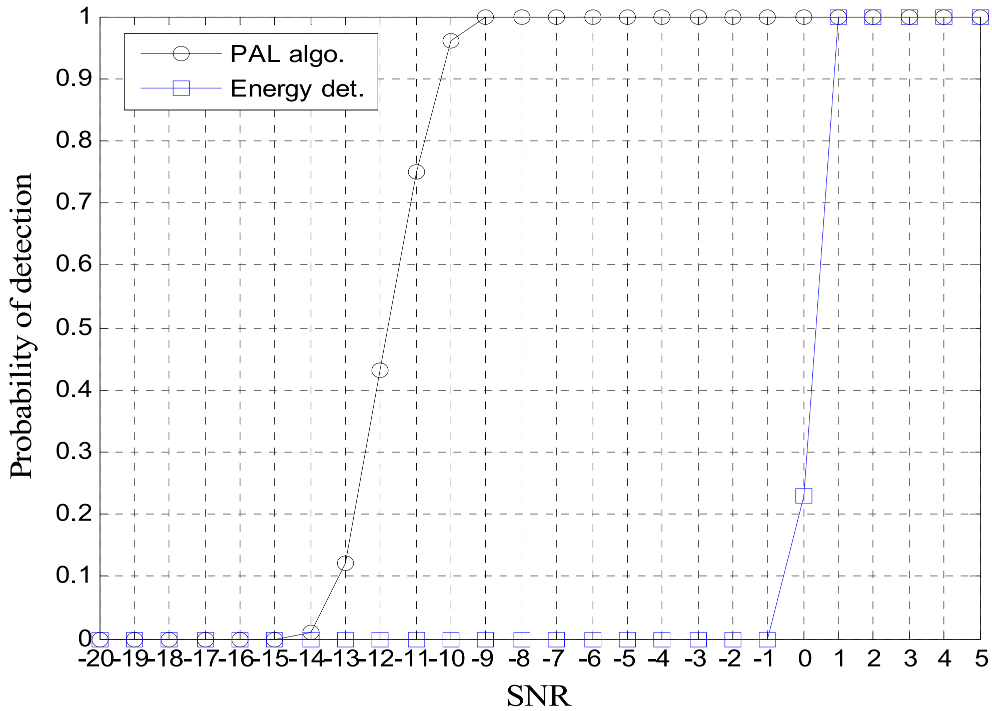

Figure 5-19: The performance of the proposed TV-PAL sensing algorithm vs. energy detector over AWGN channel and 2 dB noise uncertainty

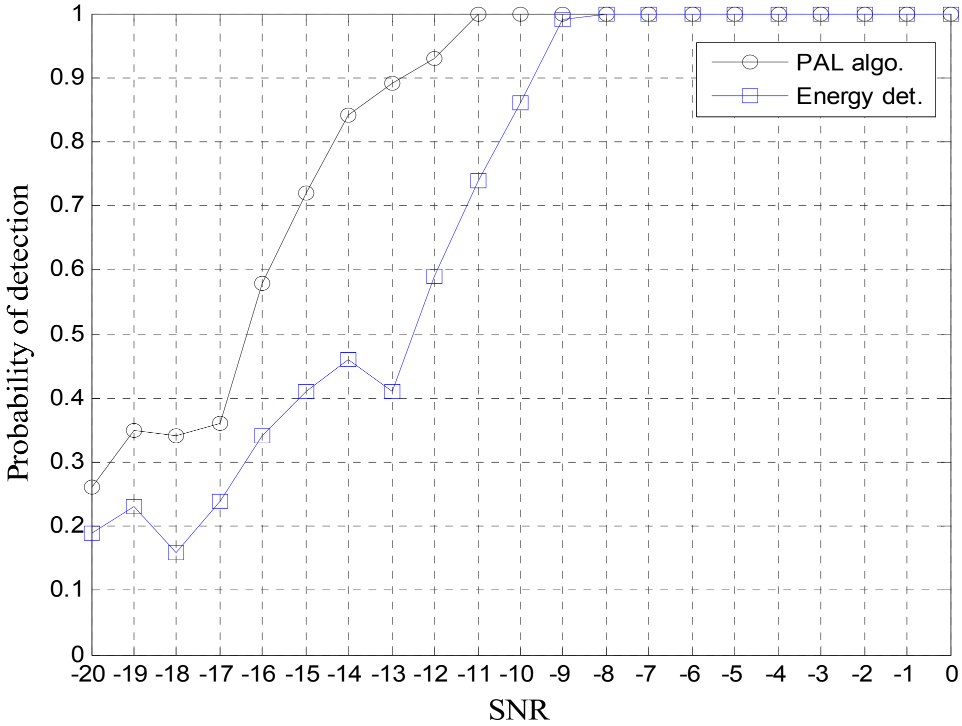

Figure 5-20: The performance of the proposed TV-PAL sensing algorithm vs. energy detector over Rayleigh channel and 0 dB noise uncertainty

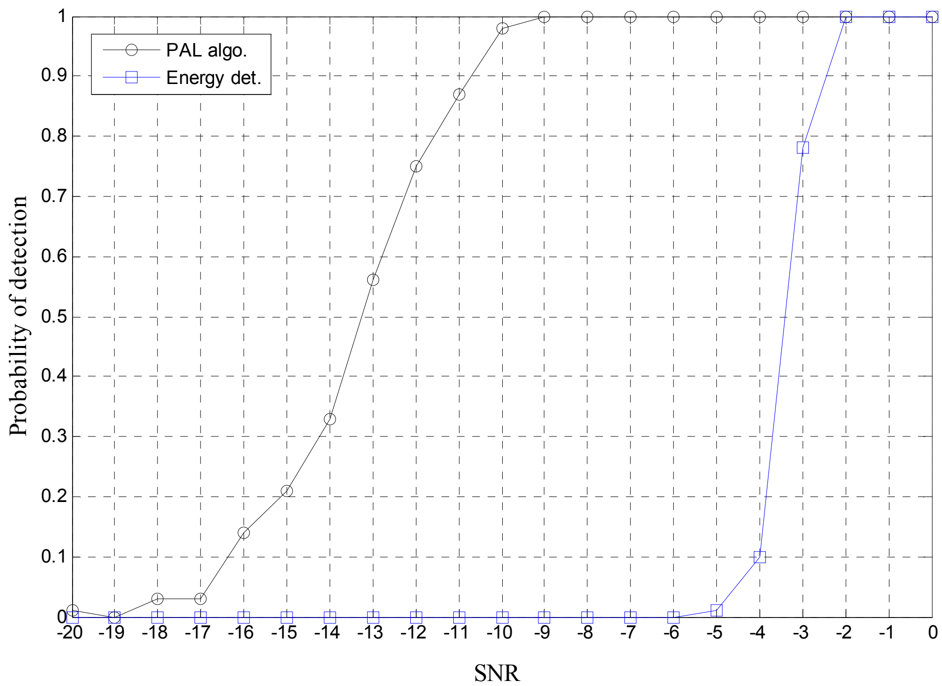

Figure 5-21: The performance of the proposed TV-PAL sensing algorithm vs. energy detector over Rayleigh channel and 1 dB noise uncertainty

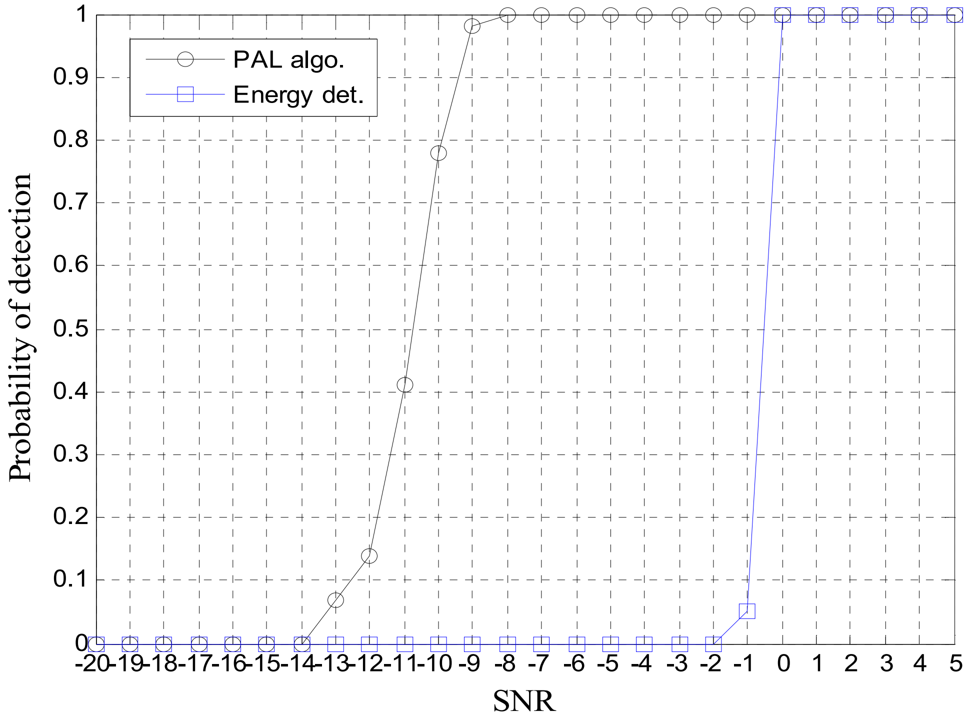

Figure 5-22: The performance of the proposed TV-PAL sensing algorithm vs. energy detector over Rayleigh channel and 2 dB noise uncertainty

As in wireless microphone sensing algorithm, this superior performance of the proposed algorithm is attributed to the same attribute that noise has no cyclostationary features making it less susceptible to noise uncertainty than energy detector.

5.4.3 Performance of Proposed Classification Approach

Performance Parameter – Probability of correct classification: The performance of this approach (the flow chart is shown in Figure 4-4) is evaluated using probability of correct classification P_c. In context of CR, P_c evaluates the ability of the classification approach to identify the type of PU which occupies the channel. In this evaluation, the same simulation parameters of previous algorithms are used. In addition to evaluate the proposed approach over AWGN, multipath fading channel profile shown in Table 5-2 is also used for the performance evaluation.

Deriving the thresholds: The thresholds λ_1 and λ_2 are determined using CDF of noise test statistics in same manner described previously.

a) *Results in AWGN*

Figure 5-23 shows the evaluation results for classification approach to distinguish TV-PAL signal over AWGN in the cases of 0, 1 and 2 dB noise uncertainties. It can be seen that the approach performs well as it is able to indentify TV-PAL signal from wireless microphone signal by 100% P_c at -12, -11 and -10 dB SNR for 0, 1, and 2 dB noise uncertainties, respectively.

For wireless microphone, Figure 5-24 shows the performance of the proposed approach to identify this signal. 100 % P_c is achieved at -10 dB SNR for the case of 0 dB noise uncertainty. For 1 and 2 dB noise uncertainty, 100% P_c is achieved at -9 dB and -8 dB SNR; respectively.

b) Results in Multipath Fading Channel

The proposed approach also performs well over Rayleigh fading channel as the results show in Figure 5-25 for TV-PAL signal and in Figure 5-26 for wireless microphone signal. For TV-PAL, the signal can be identified by 100% P_c at -13 dB SNR in the case of 0 dB noise uncertainty, while -12 dB and -11 dB SNR are required for 1 dB and 2 dB noise uncertainties. For wireless microphone signal, the proposed approach is able to identify the signal by 100 % P_c at -10 dB, -8 dB and -7 dB SNR in the cases of 0 dB, 1 dB and 2 dB noise uncertainties; respectively.

These results show the advantage of cyclostationary features not only as spectrum sensing technique but also as classification technique over AWGN and multipath fading channels with noise uncertainty.

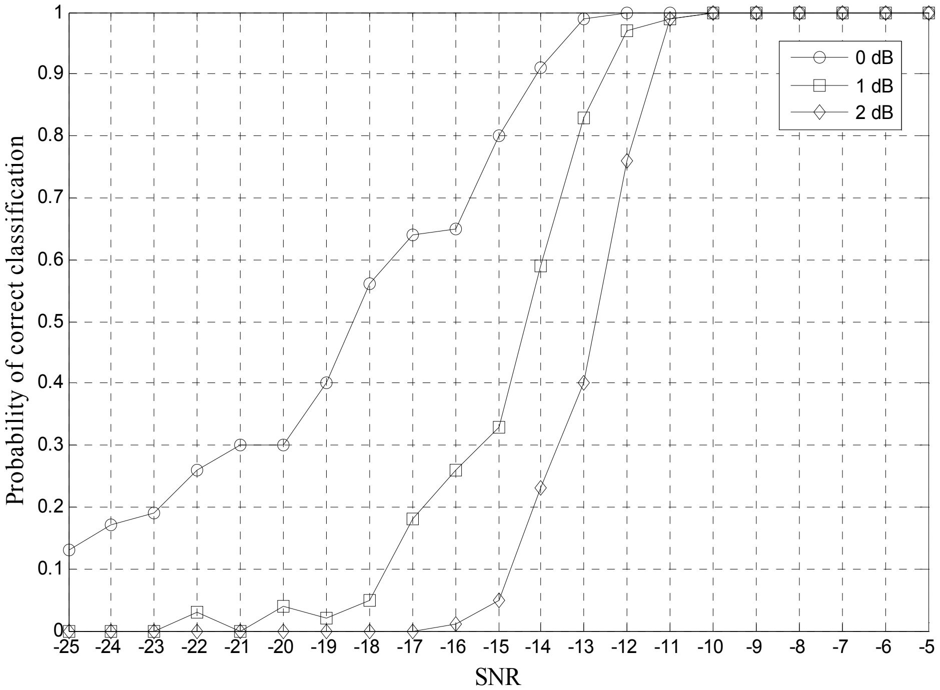

Figure 5-23: The performance of the proposed classification approach to identify TV-PAL signal over AWGN channel for 0, 1 and 2 dB noise uncertainties

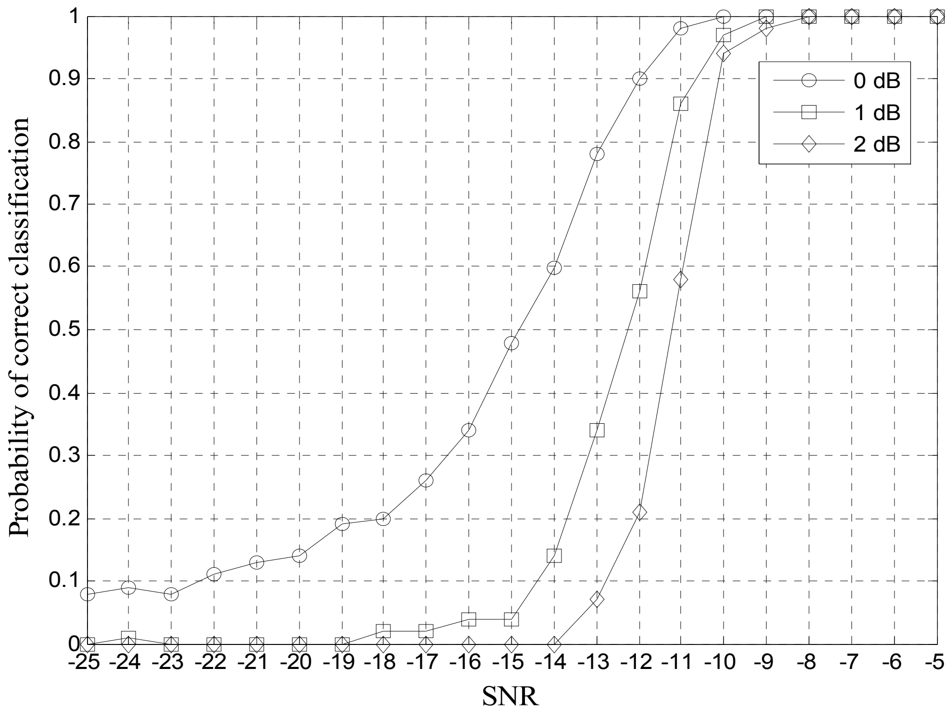

Figure 5-24: The performance of the proposed classification approach to identify wireless microphone signal over AWGN channel for 0, 1 and 2 dB noise uncertainties

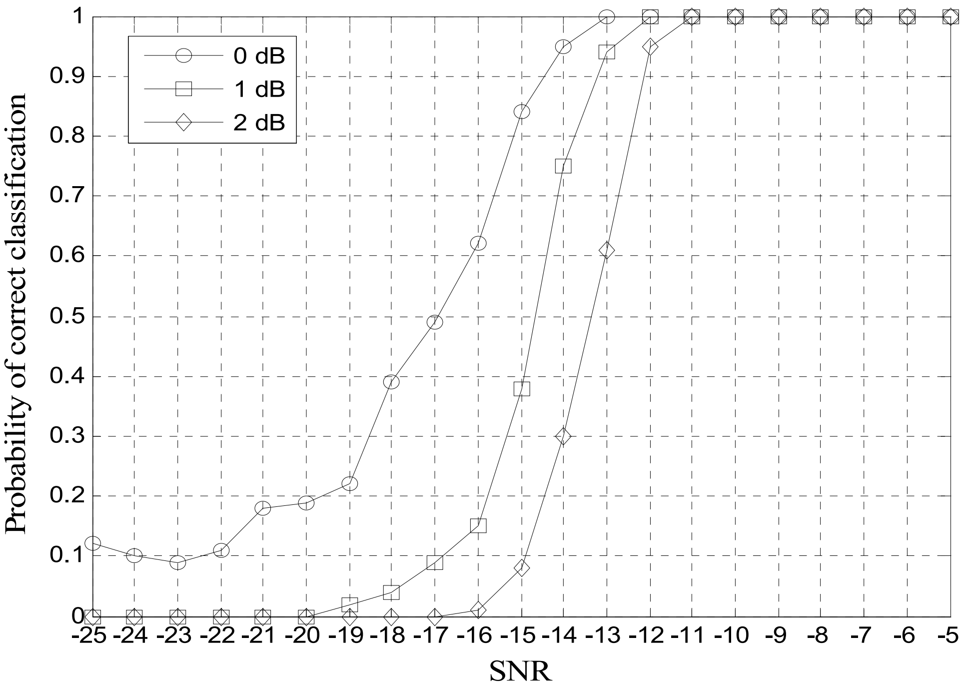

Figure 5-25: The performance of the proposed classification approach to identify TV-PAL signal over Rayleigh channel for 0, 1 and 2 dB noise uncertainties

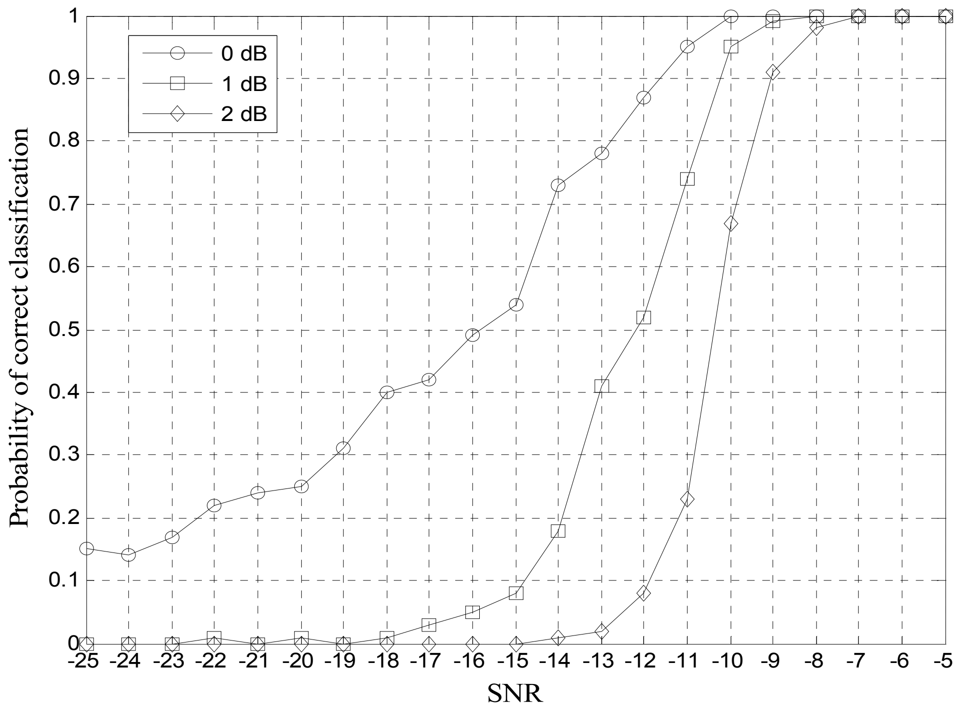

Figure 5-26: The performance of the proposed classification approach to identify wireless microphone signal over Rayleigh channel for 0, 1 and 2 dB noise uncertainties

5.5 Summary

In this chapter, the proposed algorithms in chapter 4 are evaluated over AWGN and fading channels with fixed noise uncertainties. TV-PAL and wireless microphone signals are simulated using MATLAB®. Spectrum sensing algorithms based on cyclostationary features show a good performance over AWGN and fading channels in comparison with that of energy detector whose performance degrades significantly in the case of noise uncertainty. In addition to spectrum sensing algorithm, the proposed classification approach is also evaluated and the results show that the approach is able to distinguish between TV-PAL and wireless microphone signals with high probability of correct classification.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

In this thesis, spectrum sensing for WRAN CR has been discussed. The main focus is on developing reliable algorithms for spectrum sensing by utilizing cyclostationary features of PUs. Much of the works in the area of CR do not consider analog TV-PAL system as the PU in the context of WRAN and there is no study of utilizing the cyclostationary features of TV-PAL and wireless microphone for spectrum sensing. To facilitate spectrum sensing algorithms development, an appropriate system model has been developed and a full study of co-existence scenario and RFE of sensing receiver are provided to give a complete understanding of CR spectrum sensing problem. The main objective of co-existence scenario is to find the power levels of PUs at sensing receiver. RFE architecture is also a critical design issue in CR and the work will not be complete without proposing an appropriate architecture for TV-PAL and wireless microphone signals. As in any detection problem, noise is the main impairment. Therefore, noise floor has been estimated and also noise uncertainty has been considered.

Cyclostationarity theory has been introduced with the functions that examine these features in the signal. Cyclostationary features of TV-PAL and wireless microphone are obtained using spectral correlation function. The motivation of using cyclostationarity for spectrum sensing is also stated theoretically which indicates that noise has no cyclostationary features. This fact makes the proposed algorithms perform well in noise uncertainty condition. In addition, an efficient architecture to implement spectral correlation function has been described.

Three algorithms for spectrum sensing and classification have been proposed. These algorithms are based on the obtained cyclostationarity of PUs. Features locations of spectral correlation function are used for these algorithms. Flow charts for the proposed algorithms are also explained.

The performance evaluation of the proposed algorithms is done in comparison with that of energy detector. MATLAB® simulation is used for this evaluation. The obtained results show the superior performance of the proposed algorithms in all conditions which include AWGN, fading channel and noise uncertainty.

6.2 Contribution

Here in, the contributions in current CR spectrum sensing research works are pointed as follows:

- Proposed the system model in context of IEEE 802.22 WRAN standard.
- Studied the co-existence scenario between WRAN, TV-PAL and wireless microphone systems.
- Obtained the unique cyclostationary features of TV-PAL and wireless microphone signals.
- Proposed spectrum sensing algorithms based on cyclostationary features of TV-PAL and wireless microphone.
- Classified the signals of TV-PAL and wireless microphone using their cyclostationary features
- Evaluated the performance of the proposed algorithms in term of sensitivity and classification probability.

6.3 Suggested Future Works

As such, CR is an emerging technology and there are many aspects regarding spectrum sensing that need further research work. Although, the focus has been on WRAN standard in this thesis, spectrum sensing using cyclostationary features can be used in any future CR-based applications and also can be applied to any PUs which have distinctive features. Public safety communication systems and military systems are other examples of the targeted CR-based applications where spectrum sensing is critical.

In other context of WRAN, only wireless microphone have been considered as the most common part 74 devices in the TV bands. But for real system, all part 74 devices should be considered and their cyclostationary feature should be obtained. Accordingly a possible extension of this work is to develop appropriate spectrum sensing algorithms and classification approach for these devices. Examples of part 74 devices include professional wireless intercom systems, wireless video assist systems and wireless IFB (Interrupted Feedback)

Also, we suggest further research that considers selecting thresholds for spectrum sensing algorithms adaptively based on current conditions of CR and PUs. The performance evaluation of such work should be done in order to understand the impact of this adaptability.

Finally, there is a lack of research work on the alternatives for implementing cyclostationary feature detector for CR applications. A promising implementation will be more simple and cost effective in order to be used in CPEs of WRAN systems. In this thesis, FAM method has been discussed for spectral correlation which obtains all SCF domain. This method can be enhanced in terms of complexity and speed to address the problem of spectrum sensing. One suggested enhancement is to obtain the SCF only at the distinctive features of PUs instead of all SCF domains.

REFERENCES

[1] A. McMHenry, “NSF Spectrum Occupancy Measurements Project Summary,” Shared Spectrum Company,VA,U.S.A., National Science Foundation (NSF) Award Number: ANI-0335272. August 2005.

[2] R. Etkin, A. Parekh, D. Tse, “Spectrum sharing for unlicensed bands,” *Proc. IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks*, Baltimore, MD, November 2005.

[3] C. Guo, T. Zhang, Z. Zeng and C. Feng, “Investigation on spectrum sharing technology based on cognitive radio,” *Proc. 1st International Conference on Communications and Networking in China (CHINACOM 2006)*, Beijing: IEEE Press, 2006:1-5.

[4] J. M. Peha, “Approaches to spectrum sharing,” *IEEE Communications Magazine*, pp. 10–11, February 2005.

[5] FCC, “First report and order,” in FCC Docket No. 02-48, February 2002.

[6] J. Mitola, “Cognitive radio an integrated agent architecture for software defined radio,” Ph.D. dissertation, KTH Royal Institute of Technology, Stockholm, 2000.

[7] FCC, “Unlicensed operation in the TV broadcast bands,” in Notice of Proposed Rule Making (NPRM), FCC, Docket No. 04-113, May 2004.

[8] FCC, “Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies,” in Notice of Proposed Rule Making (NPRM), FCC, Docket No. 03-322*,* December 2003.

[9] P. Kolodzy et al., “Next generation communications: Kickoff meeting,” *Proc. DARPA,* October. 17, 2001.

[10] Ian F. Akyildiz, Won-Yeol Lee, Mehmet C. Vuran, and Shantidev Mohanty," NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Computer Networks Journal (Elsevier)*, Vol. 50, pp. 2127-2159, September 2006.

[11] J. Mitola, “Cognitive radio for flexible mobile multimedia communications,” *Proc. International Workshop on Mobile Multimedia Communications (MoMuC99)*, June 1999.

[12] J. Mitola, *Cognitive Radio Architecture The Engineering Foundation of Radio XML,* John Wiley and sons Inc., Hoboken, New Jersey, 2006.

[13] S. Haykin, “Cognitive radio: brain-empowered wireless communications,” *IEEE Journal on Selected Areas in Communications,* vol. 23 (2) pp. 201–220, 2005.

[14] E. Hossain, V.K. Bhargava, *Cognitive Wireless Communication Networks*, New York, USA, Springer 2007.

[15] C. Cordeiro, K. Challapali, D. Birru and N. S. Shankar, “IEEE 802.22: An Introduction to the First Wireless Standard based on Cognitive Radios,” *J. Commun. (JCM),* pp. 38-47, April 2006.

[16] MCMC, “Technical Requirements For DTTB Operating In The Frequency Band From 510 MHz To 798 MHz,” *CMC SRSP* – 521 12, Issue 2, September 2002.

[17] F. K. Jondral, “Software-defined radio-basic and evolution to cognitive radio,” *EURASIP Journal on Wireless Communication and Networking,* Volume 2005, Issue 3, pp. 275 – 283, August 2005.

[18] D. Cabric, “Cognitive radios: system design perspective,” Ph.D’s thesis, University of California, Berkeley, 2007.

[19] R. H. Walden, "Analog-to-Digital Converters Survey and Analysis", *IEEE Journal on Selected Areas in Communications,* vol. 17(4): pp. 539-550, April 1999.

[20] R. Tandra, “Fundamental Limits of Detection in Low SNR,” Master’s Thesis, University of California Berkeley, spring 2005.

[21] S. Shellhammer, and R. Tandra, “Performance of the power detector with noise uncertainty,” *IEEE 802.22-06-0134-00-0000*, July 2006.

[22] S. Shellhammer, “Performance of the Power Detector,” *IEEE 802.22-06/0075r0*, May 2006.

[23] H. Urkowitz, “Energy detection of unknown deterministic signals,” *Proc. IEEE*, vol. 55, pp. 523–531, 1967.

[24] F. Digham, M. Alouini, M. Simon, “On the energy detection of unknown signals over fading channels,” *Proc. IEEE ICC 2005*, vol. 5, pp. 3575–3579, May 2003.

[25] D. Cabric, S.M. Mishra, R.W. Brodersen, “Implementation issues in spectrum sensing for cognitive radios,” *Proc. 38th Conference on Signals, Systems and Computers 2004*, pp. 772–776, November 2004.

[26] D. Cabric, A. Tkachenko, R. W. Brodersen, “Spectrum Sensing Measurements of Pilot, Energy and Collaborative Detection,” *Proc. IEEE Milcom 2006,* October 23-25, 2006.

[27] A. Sahai, N. Hoven, R. Tandra, "Some fundamental limits on cognitive radio," *Proc. 42nd Allerton Conference on Communication, Control, and Computing*, Monticello, IL, October 2004.

[28] W. Gardner, "The spectral correlation theory of cyclostationary time series," *EURASIP Signal Processing,* Vol. 11, pp. 13-36, 1986.

[29] W. A. Gardner, *Statistical Spectral Analysis: A Non-probabilistic Theory,* Englewood Cliffs, NJ: Prentice-Hall, 1987.

[30] W. Gardner, "Signal interception: a unifying theoretical framework for feature detection," *IEEE Trans. Commun*., vol. 36(8), pp. 897–906, 1988.

[31] W. A. Gardner, "Exploitation of spectral redundancy in cyclostationary signals," *IEEE Signal Processing Magazine*, vol. 8, no. 2, pp. 14-36, April 1991.

[32] W. A. Gardner and C. M. Spooner, "Signal interception: Performance advantages of cyclic-feature detectors," *IEEE Trans. Commun.,* Vol. 40, pp. 149-159, January 1992.

[33] H. Chen, W. Gao and D. G. Daut, "Spectrum sensing using cyclostationary properties and application to IEEE 80.22 WRAN," *Proc. GLOBECOM '07*, pp. 3133-3138, November 2007.

[34] L. P. Goh, Z. Lei, and F. Chin, "DVB detector for cognitive radio," *Proc. IEEE ICC 2007*, pages 6460-6465, June 2007.

[35] S. H. Sohn, N. Han, J. M. Kim, and J. W. Kim, "OFDM signal sensing method based on cyclostationary detection," *Proc. Crowncom 2007*, Orlando, Florida, USA, July-August 2007.

[36] H. S. Chen, W. Gao, and D. Daut, "Spectrum sensing for wireless microphone signals," *5th IEEE Annual Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks Workshops, 2008. SECON Workshops '08*, pp. 1–5, June 2008.

[37] N. Han, S. H. Shon, J. H. Chung and J. M. Kim, "Spectral correlation based signal detection method for spectrum sensing in IEEE 802.22 WRAN systems," *Proc. IEEE conf. ICACT 2006,* vol. 3, pp. 6-11, February 2006.

[38] J. K. Lee, J. H. Yoon, J.-U. Kim, "A new spectral correlation approach to spectrum sensing for 802.22 WRAN system," *Proc. The 2007 International Conference on Intelligent Pervasive Computing (IPC 2007)*, pp. 101-104, 2007.

[39] B. Wild and K. Ramchandran, "Detecting primary receivers for cognitive radio applications," *Proc. IEEE DySPAN, 2005*, pp. 124-130, November 2005.

[40] G. Ganesan, Y.G. Li, "Cooperative spectrum sensing in cognitive radio networks," *Proc. IEEE DySPAN 2005*, pp. 137–143 November 2005.

[41] A. Ghasemi, E. S. Sousa, "Collaborative spectrum sensing for opportunistic access in fading environment," *Proc. IEEEDySPAN 2005,* pp. 131–136, 2005.

[42] J. Zhao, H. Zheng, G. H. Yang, "Distributed coordination in dynamic spectrum allocation networks," *Proc. IEEE DySPAN 2005,* pp. 259–268, November 2005.

[43] H. Tang, "Some physical layer issues of wide-band cognitive radio systems," *Proc. IEEE Int. Symposium on New Frontiers in Dynamic Spectrum Access Networks,* Baltimore, Maryland, USA, pp. 151–159, November. 2005.

[44] Z. Tian and G. B. Giannakis, "A wavelet approach to wideband spectrum sensing for cognitive radios," *Proc. of IEEE Int. Conf. Cognitive Radio Oriented Wireless Networks and Commun. (Crowncom),* Mykonos Island, Greece, June 2006.

[45] Y. Youn, H. Jeon, J. Choi, H. Lee, "Fast spectrum sensing algorithm for 802.22 WRAN Systems," *Proc. of ISCIT '06 International*, September 2006.

[46] Y. Hur, J. Park, W. Woo, K. Lim, C. Lee, H. Kim, and J. Laskar, "A wideband analog multi-resolution spectrum sensing (MRSS) technique for cognitive radio (CR) systems," *Proc. IEEE Int. Symp. Circuits and Systems*, Island of Kos, Greece, pp. 4090–4093, May 2006.

[47] F. Sheik, B. Bing, "Cognitive spectrum sensing and detection using polyphase DFT filter banks," *Proc. IEEE Consumer Communication and Networking Conference (CCNC),* pp. 973-977, 2008.

[48] J. Hoffmeyer, "Regulatory and Standardization Aspects of DSA Technologies – Global Requirements and Perspectives," *Proc. IEEE DySPAN,* Baltimore, November 2005.

[49] G. Chouinard, "WRAN reference model," *IEEE 802.22-04-0002-15-0000,* January 2007.

[50] G. Chouinard, "WRAN keep-out region," *IEEE 802.22-06-0052-03-0000*, May 2006.

[51] [Online]. Available: http://www.fcc.gov/mb/audio/bickel/curves.html, March 2009.

[52] G. Chouinard, "WRAN sensing receiver characteristics," *IEEE 802.22-06-0102-01-0000,* June 2006.

[53] S. M. Kay, *Fundamentals of statistical signal processing: Detection theory*, Upper Saddle River, New Jersey, USA: Prentice-Hall, 1998, vol. 2.

[54] IEEE 802.22 Working Group on Wireless Regional Area Networks, [Online]. Available: http://www.ieee802.org/22/, June 2007.

[55] L. W. Couch, *Digital and Analog Communication System*, Prentice Hall, Inc. Upper Saddle River, NJ, 2001.

[56] R. R.Gulati, *Colour Television Principles and Practice*, New Age Ltd., India, 1992.

[57] J. Eargle, *The Microphone Book*, Linarce House, Jordan Hill, Oxford, 2005.

[58] E. Reihl, "Wireless microphone characteristics," *IEEE 802.22-06-0070-00-0000,* May 2006.

[59] A. V. Oppenheim, R. W. Schafer and J. R. Buck, *Discrete-Time Signal Processing 2nd Edition*, Prentice Hall: Upper Saddle River, NJ, 1999.

[60] W. A. Brown, H. H. Loomis, "Digital implementations of spectral correlation analyzers," *IEEE Trans. on SP*, Vol. 41, NO. 2, pp. 703-720, February 1993.

[61] R. S. Roberts, W. A. Brown, and H. H. Loomis, Jr., "Computationally efficient algorithms for cyclic spectral analysis," *IEEE Signal Processing Magazine*, vol. 8, no. 2, pp. 38-49, April 1991.

[62] L.P. Goh, Z. Lei, and F. Chin, "DVB detector for cognitive radio," *Proc. of the IEEE ICC 2007, pp. 6460-6465*, June 2007.

[63] C. Stevenson, C. Cordeiro, E. Sofer and G. Chouinard, "Functional requirements for the 802.22 WRAN standard," *IEEE 802.22-05-0070-48-0000,* November 2006.

[64] E. Sofer and G. Chouinard, "WRAN channel modeling," *IEEE 802.22-05-0055-07-0000*, September 2005.

PUBLICATIONS

1. A. Mossa, V. Jeoti, " WRAN cognitive radio and cyclostationary features of analog TV and wireless microphone," In Proc. of the IEEE SCOReD 2008, Malaysia, November 2008, ISBN: 978-1-4244-2869-4.
2. A. Mossa, V. Jeoti, " Cyclostationarity-based spectrum sensing for analog TV and wireless microphone signals," In Proc. of the IEEE CICSyN 2009, pp.380-385, Indore, India, July 2009, ISBN: 978-0-7695-3743-6.
3. A. Mossa, V. Jeoti, "Cognitive radio: cyclostationarity-based classification approach for analog TV and wireless microphone signals," In Proc. of the IEEE CITISIA 2009, pp. 107-111, Malaysia, July 2009, ISBN: 978-1-4244-2887-8.
4. A. Mossa, V. Jeoti, " The evaluation of cyclostationarity-based spectrum sensing in multipath fading channel," submitted for publication in ICIAS 2010, June 2010.
5. B. Adoum, A. Mossa, V. Jeoti, "Discrete wavelet packet transform based multiresolution spectrum sensing (MRSS) using cyclostationary feature detector," submitted for publication in ICIAS 2010, June 2010.
6. A. Mossa, V. Jeoti, "WRAN primary users classification performance in multipath fading channel," submitted for publication in ITSIM 2010, June 2010.
7. A. Mossa, V. Jeoti, "Cognitive Radio: cyclostationary features of TV-PAL and wireless microphone for WRAN applications," to be submitted to Signal Processing: An International Journal (SPIJ).