UNIVERSITI PUTRA MALAYSIA

ENERGY DETECTION FOR SPECTRUM SENSING IN OFDM-BASED COOPERATIVE AND NON-COOPERATIVE RADIO NETWORKS

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ENERGY DETECTION FOR SPECTRUM SENSING IN OFDM-BASED COOPERATIVE AND NON-COOPERATIVE RADIO NETWORKS

By

EMAD HMOOD SALMAN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

October 2018

DEDICATION

To The memory of my Mother and Father,

To my

Wife, my great woman, My Soul, heart, mind … and everything,

Adorer, Maha that love me and always pray to me.

Kids, the flavor of my life,

Sisters and Brothers, my real family,

Country, Iraq, country of ethics, sciences, and Martyrs,

Second country, Malaysia, country of development, progress, and technology

"Without Your Support and Encouragement, supporting, and Praying My Success Would not have Been Possible."

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

ENERGY DETECTION FOR SPECTRUM SENSING IN OFDM-BASED COOPERATIVE AND NON-COOPERATIVE RADIO NETWORKS

By

EMAD HMOOD SALMAN

October 2018

Chairman : Professor Nor Kamariah Noordin, PhD
Faculty : Engineering

The Cognitive Radio (CR) concept aims to opportunistically access the different bandwidths of wireless spectrum with preventing harmful interference to the licensed users to address the fixed bands access issue. The Spectrum Sensing (SS) stage is crucial in CR system to reliably estimate the presenting of licensed user. This stage can be performed thorough several techniques to reuse the OFDM signal in 4G and 5G systems. The Energy Detection (ED) technique is the simplest and low computational complexity. However, it has some challenges in low Signal-to-Noise Ratio (SNR). In this thesis, we address the challenges in addition to reduce the computational complexity and improve the detection accuracy.

Firstly, a new approximated closed-form expression is derived for the non-cooperative SS (NSS) based on ED technique to sense an OFDM signal. With the purpose of low SNR effect reduction, the expression is presented a novel Constant Local False Alarm Rate (CLFAR) with Constant Local Detection Rate (CLDR) algorithm, in which Secondary User (SU) can detect the licensed band in high noise variance medium accurately. Next, we developed a Constant Global False Alarm Rate (CGFAR) with Constant Global Detection Rate (CGDR) algorithm to mitigate the Cooperative SS (CSS) requirements. This algorithm can also work for big number of SUs that detect the OFDM signal. The last but not least, a new scheme of Modified Compressive SS (COMPSS) technique, proposed to significantly decrease the consumed power in Analog-to-Digital Convertors (ADCs). These stages are the Wavelet Transform based on pyramid algorithm, and the previous algorithms to apply this system on NSS and CSS networks. This cascaded COMPSS system does not require any signal reconstruction although it reduces the sub-Nyquist rate.

Simulation results show that the analysis on the first algorithm has precise sensing and enhances the detection performance in low SNR case till -50 dB. In addition, it decreases the computational complexity. Moreover, the second algorithm improves the global decision through realizing the desired detection performance with low computational complexity. Besides, the number of SUs can be increased to 100 users. The cascaded system can compress and sense the licensed wideband with compression ratio till to 81.5% for one and multi SUs. The analytical results are validated the simulation results.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doctor Falsafah

PENGESANAN TENAGA UNTUK PENDERIAAN SPEKTRUM DALAM RANGKAIAN RADIO KOPERASI DAN BUKAN-KOPERASI

Oleh

EMAD HMOOD SALMAN

Oktober 2018

Pengerusi : Profesor Nor Kamariah Noordin, PhD
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Konsep Radio Kognitif (CR) bertujuan untuk mengakses jalur lebar spektrum tanpa wayar yang berbeza dengan menghalang gangguan berbahaya kepada pengguna berlesen untuk menangani isu akses jalur tetap. Tahap Sensing Spektrum (SS) adalah penting dalam sistem CR untuk menganggarkan secara pasti penyampaian pengguna berlesen. Tahap ini boleh dilakukan beberapa teknik menyeluruh untuk menggunakan semula isyarat OFDM dalam sistem 4G dan 5G. Teknik Pengesanan Tenaga (ED) adalah kerumitan komputasi yang paling sederhana dan rendah. Walau bagaimanapun, ia mempunyai beberapa cabaran dalam Nisbah Signal-to-Noise (SNR) yang rendah. Dalam tesis ini, kita menangani cabaran di samping mengurangkan kerumitan komputasi dan meningkatkan ketepatan pengesanan.

Pertama, ekspresi bentuk tertutup yang baru diperolehi untuk SS (NSS) bukan koperasi berdasarkan teknik ED untuk merasakan isyarat OFDM. Dengan tujuan pengurangan kesan SNR yang rendah, ungkapan itu dibentangkan sebagai novel Penggantian False Local False Rate (CLFAR) dengan algoritma Rate Detector Local Constant (CLDR), di mana Pengguna Sekunder (SU) dapat mengesan band berlesen dalam medium variance noise yang tinggi dengan tepat. Seterusnya, kami membangunkan Kadar Penggera Global Berterusan (CGFAR) dengan algoritma Pengesanan Global Tetap (CGDR) untuk mengurangkan keperluan Koperasi SS (CSS). Algoritma ini juga boleh berfungsi untuk sejumlah besar Sus yang mengesan isyarat OFDM. Yang terakhir tetapi paling tidak, skim baru Modified Compressive SS (COMPSS), yang dicadangkan untuk mengurangkan secara signifikan kuasa yang digunakan dalam Pengubah Analog-untuk-Digital (ADCs). Tahap-tahap ini adalah Transform Wavelet berdasarkan algoritma piramid, dan algoritma sebelumnya untuk menerapkan sistem ini pada rangkaian NSS dan CSS. Sistem cas ini melengkapkan sistem COMPSS tidak memerlukan sebarang pembinaan semula isyarat walaupun ia mengurangkan kadar sub-Nyquist.

Hasil simulasi menunjukkan bahawa analisis pada algoritma pertama mempunyai penderiaan yang tepat dan meningkatkan prestasi pengesanan dalam kes SNR yang rendah hingga -50 dB. Di samping itu, ia mengurangkan kerumitan pengiraan. Selain itu, algoritma kedua meningkatkan keputusan global dengan menyedari prestasi pengesanan yang diingini dengan kerumitan komputasi yang rendah. Selain itu, jumlah SU boleh ditingkatkan kepada 100 pengguna. Sistem cascaded dapat memampatkan dan merasakan wideband berlesen dengan nisbah mampatan hingga 81.5% untuk satu dan multi SU. Keputusan analisa disahkan hasil simulasi.

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Last but not least, I would like to thank my family for their endless support encouragement and love. Most of this work occurred on weekends, nights, while on vacation, and other times inconvenient to them.

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

16-QAM	16-quadreture amplitude modulation
ADC	Analog to digital converter
AWGN	Additive white Gaussian noise
BPSK	Binary phase shift keying
BPF	Band pass filter
CR	Cognitive radio
CRN	Cognitive radio network
CSS	Cooperative spectrum sensing
COMP	Compressed spectrum sensing
CDCT	Compact discrete cosine transform
CAF	Cyclic autocorrelation function
CSD	Cyclic spectral density
CDF	Cumulative distribution function
CMFB	Cosine modulated filter bank
CLFAR	Constant local false alarm rate
CLDR	Constant local detection rate
Crocor-Rel	Cross-correlation Relation
CGFAR	Constant global false alarm rate
CGDR	Constant global detection rate
DST	Discrete sine transform
DDWT	Discrete Daubechies wavelet transform
DVB	Digital video broadcast

DSA	Dynamic spectrum access
DRiVE	European dynamic radio for IP services in vehicular environments
DARPA	US Defence Advanced Research Projects Agency
DWT	Discrete wavelet transform
DCT	Discrete cosine transform
DFT	Discrete Fourier transform
DCOMP	Distributed COMP
DWPT	Discrete wavelet packet transform
ED	Energy detection
EM	Expectation-maximisation algorithm
EWT	Empirical wavelet transform algorithm
FFT	Fast Fourier transform
FCC	Federal Communications Commission
FC	Fusion centre
HSDPA	High-Speed Downlink Packet Access
HSPA	High Speed Packet Access
HDF	Hard decision fusion
i.i.d	Independent and identically distributed random process
JCOMP	Jointly COMP
LAP	Aerial low altitude platform
MCMC	Malaysian Communications and Multimedia Commission
MAC	Media access control layer
MWC	Modulated wideband converter

OCRA	OFDM-based cognitive radio network
OFDM	Orthogonal frequency division multiplexing
PF	Parallel fusion
PSD	Power spectral density
PU	Primary users
QPSK	Quadrature phase shift keying
QoS	Quality of service
QAM	Quadrature amplitude modulation
ROC	Receiver Operating Characteristics
SS	Spectrum sensing
SA	Spectrum access
SU	Secondary user
SNR	Signal to noise ratio
SWT	Stationary wavelet transform
TV	Television
USS	Uncooperative spectrum sensing
UMTS	Universal Mobile Telecommunications System
WS	White space
WHT	Welch Hadamard transform,
WT	Wavelet transform
WB	Wavelet Bases

LIST OF SYMBOLS

a[n]	Time domain stream
$A[k]$	DCT stream
N	Length of signal
K	Length of transformed signal
H_0	Hypothesis for idle PU signal
H_1	Hypothesis for busy PU signal
$w[n]$	Gaussian noise
σ_w^2	Variance of noise
$s[n]$	Transmitted PU signal without noise
σ_s^2	Variance of s
$x[n]$	Received PU signal
ξ	Test statistic
η	Predefined threshold
P_f	Probability of false alarm
P_{md}	Missed detection probability
P_d	Probability of detection
$\Phi_{H0}(\eta)$	CDF of ξ under H_0
$\Phi_{H1}(\eta)$	CDF of ξ under H_1
$Q(.)$	Tail probability of the standard normal distribution
Q_d	Global detection probability
Q_f	Global false alarm probability
nsu	Number of cooperating SUs
ψ	Spread bases

s	Extension of signal
M	Number of column
Φ	Sensing matrix
y	Represents the measurements of signal
$\tilde{x}$	Reconstructed signal
En	Energy
T_0	Signal interval
N_0	Signal length of discrete PU signal
$x(t)$	Continuously received signal
f_c	Central frequency
BW	Bandwidth
PSD_{FFT}	Power spectral density for raw periodogram
$X[k]$	Frequency domain of $x[n]$
$Y[k]$	Frequency domain of $x[n]$ with shorter length $Ne < N$
PSD_{CDCT}	Power spectral density for CDCT periodogram
γ	SNR of received PU signal
α	Length ratio
P_e	Probability of error
Z_{XY}	Cross-correlation stream
G	Reverse of the cyclic prefix ratio
ϵ	Vanished Power ratio
P_{fcss}	Local probability of a false alarm in the CSS-MCDCT algorithm
P_{dcss}	Local probability of detection in the CSS-MCDCT algorithm

Q_e	Global probability of error
Q_{md}	Global miss detection probability
New	Compressive stream length (length of Z), *New* << *N*
y_{COMP}	Compressed signal of x_{COMP}
Φ_1	DDWT matrix
s_1	Scaling function of pyramid DDWT
$w_{1 \ldots 1023}$	Wavelet coefficients of pyramid DDWT
Y	Wavelet coefficients matrix contains only traffic
N_{COMP}	Length of Y
Φ_{DDWT}	Pyramid discrete Daubechies wavelet transform matrix
Φ_{DCDT}	CDCT transform matrix
Z	Compressive coefficients stream
PSD_{COMP}	Power spectral density for hybrid compression algorithm
ϵ_h	Higher vanished Power ratio
ϵ_l	Lower vanished Power ratio

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

SIn the last decade, the cognitive radio (CR) concept has attracted a lot of interest ever since it was used for efficiently utilising spectrum, enabling coexistence for different wireless networks, weakening harmful interference, and increasing reliable wireless services. Cognitive radio network (CRN) schemes can be divided into two types, as shown in Figure 1.1: CRN without infrastructure, and CRN with infrastructure. The difference between the two is that the second type contains a secondary base station and a spectacular spectrum. In general, both networks do not require any authorisation to work and they are used as accessible spectrum in an opportunistic manner [1]. To perform the work of these networks, one of the main tasks of CR is to achieve spectrum sensing (SS). The function of SS is to observe a licensed spectrum, sense it, and decide whether it is busy or idle. This process is called SS, or more specifically, non-cooperative spectrum sensing (NSS), where it is performed by one CR user (also called secondary user, SU). However, the NSS process has some setbacks like hidden terminal problem, poor detection performance, and detection uncertainty. To address this, the SS can be carried out by more than one CR user, which is called cooperative spectrum sensing (CSS) [2].

Since the rapid development of services offered by current wireless communication technologies, electromagnetic spectrum resources have become more and more scarce. In recent years, these technologies have not been able to handle the increasing demands of huge amounts of data. This problem can be seen in the overcrowded Malaysian spectrum allocation chart, as depicted in Figure 1.2 as provided by the Malaysian Communications and Multimedia Commission (MCMC) [3]. From Figure 1.2, it can be observed that an overcrowded spectrum that is licensed by governmental and other types of owners can lead to a lack in spectrum resources, especially for those below 3 GHz bands. To address these issues, several conventional SS techniques that contain both benefits and limitations were designed. Unfortunately, the limitations in these techniques are substantial and thus they should be reduced as much as possible [4]. On the other hand, compressed spectrum sensing (COMPSS) is one of the more desirable approaches for sensing the wideband signals. The COMPSS techniques suffer from high computational complexity for both its techniques; matrix sensing and recovery approaches [5].

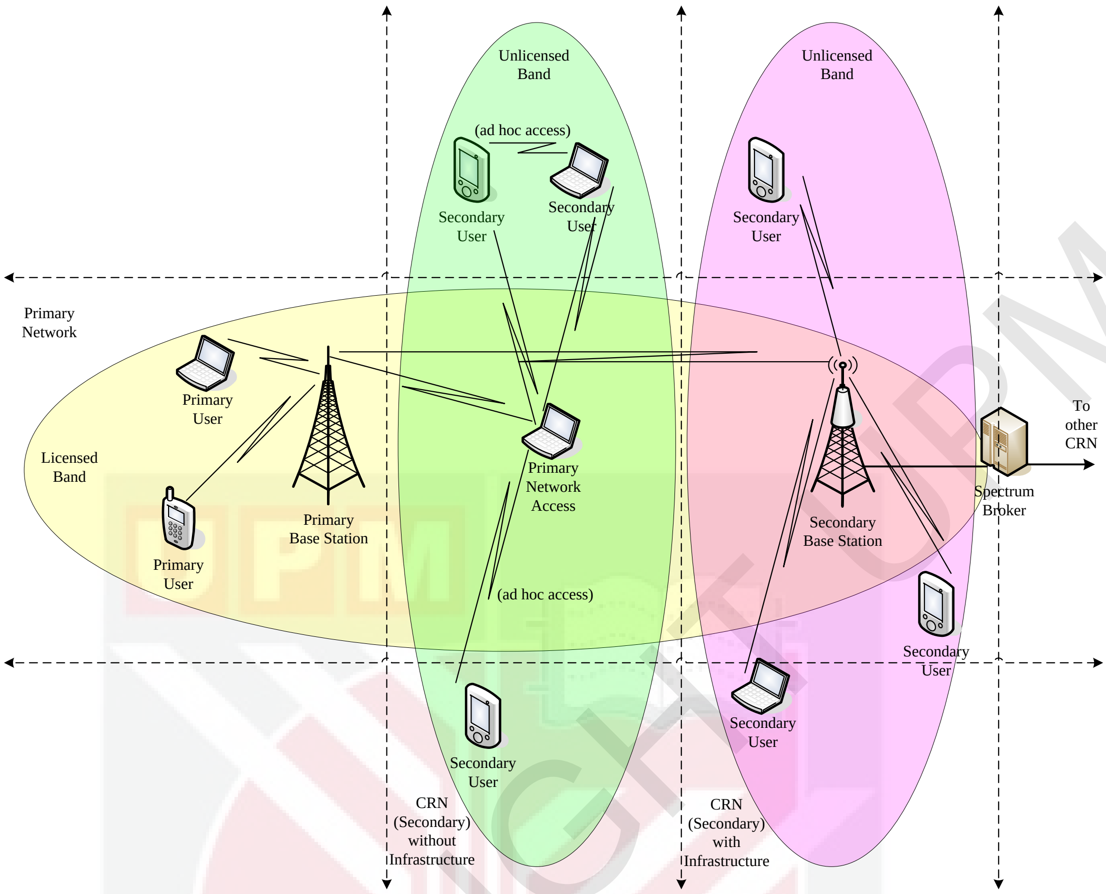

Figure 1.1 : The CR Network Architecture

In the literature, some related studies have proposed algorithms to solve the issue of the lack of spectrum. G. Yang, *et al.*, (2016) [6] did a study on an SS scheme based on normalising energy detection (ED) to decrease the signal to noise ratio (SNR) wall. This scheme was applied on two types of channel: additive white Gaussian noise (AWGN) and Rayleigh fading. This scheme also showed good detection performance, but it required high computational complexity. Another ED scheme was proposed for two cascaded Rayleigh fading channels by deriving a computational model for such type of channel [7]. However, this model has computational complexity and a bad performance for low SNR.

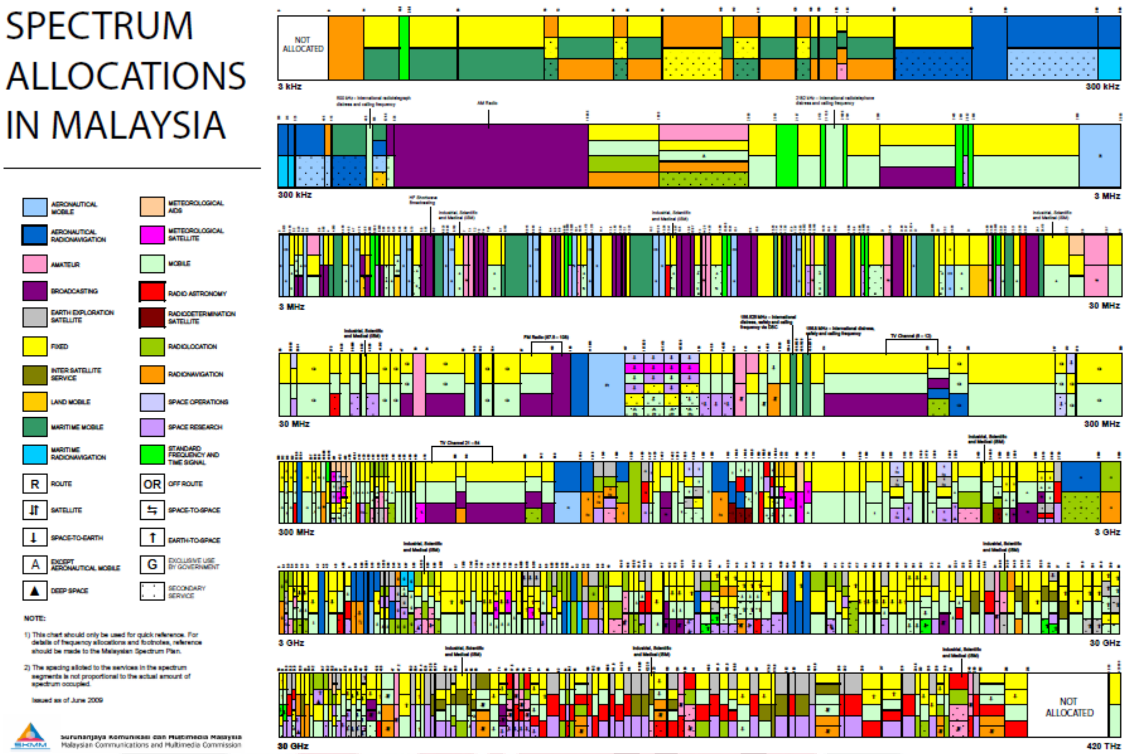

Figure 1.2 : Spectrum Allocations in Malaysia [3]

F. Li, *et al.*, (2016) [8] built a COMPSS algorithm using discrete sine transform (DST) and OR-rule for CSS networks, but this algorithm showed poor performance for SNR < -5 dB. In the studies conducted by H. Al-Hmood and H. S. Al-Raweshidy, (2017) and S. E. El-Khamy, M. B. Abd-el-Malek, and S. H. Kamel, (2017) [9, 10], an ED based on mixture γ distribution algorithm was investigated. However, it also required computational complexity and showed poor performance at low SNR. Another investigation was carried out on COMPSS using a stationary wavelet transform (SWT) scheme since it has a simple computational model, but it does not good in lower SNR [10]. Lastly, a maximum inner product COMPSS algorithm was derived for big compression ratio by S. Ren, Z. Zeng, C. Guo, and X. Sun, (2017) [11]. However, the detection performance for this algorithm was poor at SNR < -5 dB. Thus, the ED-based SS and COMPSS-proposed techniques failed to make a trade-off between increasing the benefits and decreasing the effects of the limitations.

1.2 Problem Statement

Traditional SS techniques in CRNs use spectrum to expand the capacity of various wireless systems in order to handle huge rates of data transmission. This transmission may be achieved using orthogonal frequency division multiplexing (OFDM) signal. Although good performance in detection capability is an advantage of such techniques, they are hampered by computational complexity and a high SNR wall. Moreover, in CRNs, the raw COMPSS techniques provide wideband signals to the wireless networks that need them. However, these techniques have a small compression ratio rather than computational complexity, resulting in high energy consumption in front-end receivers. The problems that will be addressed throughout this thesis are listed as follows:

1. In the OFDM systems, its spectra that can be reused in 4G and 5G systems, must be sensed actively and precisely. By using one SU, many problems should be addressed during sensing process to deliver a smooth licensed (PU) signal with high quality. However, the traditional NSS techniques that play a major role in CRNs have many drawbacks during the OFDM signal detection process in the wireless systems, such as high noise variance, poor detection performance, high system error, and big computational complexity [69].
2. The wireless communication networks that are need to OFDM signals such as of 4G and 5G in transmission need to spectra to avoid the congestions and the lack in spectra and then ensuring the transmission service. Nevertheless, the conventional CSS approaches, which CRNs currently use have poor detection performance in low SNR during the OFDM signal detection process. Moreover, these approaches have trade-off problems among a number of secondary users, computational complexity, global detection performance, and detection error [72].
3. The OFDM signals based wideband require high-cost front ends for sensing rather than receiving it and then large power will be consumed in. Thus, pollution will be created due to the large power consumption for both cases of CRNs; one SU and multi-SUs. In addition, the raw COMPSS techniques that are required for sensing the wideband signals showed high power consumption in the receiver front end for one [10] or more secondary users [80] in CRNs. These techniques also have high computational complexity and non-accurate signal measurement.

1.3 Research Objectives

In contrast to COMPSS techniques, most current SS techniques have failed to consider some factors such as coherency, pre-known data requirement, detection performance, computational complexity, compression ratio, and SNR wall. These techniques are applied either for USS or for CSS that work in various wireless communication networks. In a nutshell, this thesis aims to achieve the following specific objectives:

1. To design a new NSS technique to sense OFDM signal reliably with different kinds scenarios of mappers. The proposed technique should be decreased the noise variance, improved the detection performance, and reduced the error of USS technique, and simplified the computational complexity level in a CRN.
2. To develop a new CSS technique to sense OFDM signal, which will be sensed by more than one SU during same network. The new proposed technique should make a trade-off among enhancing the global detection performance, increasing the number of secondary users, and reducing the error of CSS technique, and simplifying computational complexity level in a CRN.

3. To design new COMPSS techniques for sensing OFDM signal based on one SU detection and multi SUs detection, respectively. In both proposed technique, many issues should be addressed such as decreasing the power consumption, improving the compressive detection performance, reducing the error of signal measurement, and simplifying computational complexity level in a CRN.

1.4 Scope of the Thesis and its Significance

This thesis focuses on providing wireless communication networks with unlicensed spectrum by temporarily sensing OFDM signal. The scope of this thesis is detailed in Figure 1.3 which shows the CRN of previous work focuses on the type of CRN that does not have an infrastructure. The solid lines denote the direction followed in this thesis to achieve its aims and objectives while the dotted lines denote the other research fields, which are beyond the scope of this thesis.

Traditional solutions have many drawbacks as each solution addresses only one or two issues. Other networks that communicate using the wideband spectrum also face the same challenges. As the 5G network promises to send and receive data incoherency, the solution must therefore also be able to transmit incoherency, especially since it has a responsibility to handle larger amounts of data. In view of the above, it would be an excellent solution to these issues if a CRN can be designed which can sense a spectrum with high accuracy, low cost and at low SNR. It would also be a remarkable achievement to implement a CRN that can sense a wideband spectrum with high accuracy and lower power consumption. Both these solutions must be workable in incoherent conditions in order to handle the 5G networks.

Thus, for one SU only, the sensing procedure of OFDM spectrum should be divided into two kinds according to signal type; narrowband and wideband. The first kind will be sensed by using the energy detection technique, whereas the second one will be sensed by using the sub-Nyquist sampling without reconstruction technique. On the other hand, both techniques are upgraded to deal with more than one SU case for centralized cooperative cognitive radio networks. The upgraded techniques are employed the soft decision fusion and OR-rule to achieve a better detection performance with maximum SUs number.

1.5 Research Methodology

Based on the aforementioned objectives, the main aims of this thesis were achieved using methods which are explained in three separate chapters (Chapters 3, 4 and 5), as shown in Figure 1.4.

Chapter 3 details the designing of NSS algorithms for solving the SS issues and problems which previously have not been effectively and carefully solved. To achieve the first objective, an analytical model of the NSS technique is developed for sensing the OFDM signal. According to the ED-frequency domain approach, the model derived at is a closed-form expression model for evaluating the power spectral density (PSD) using compact discrete cosine transform (CDCT) filter, which is the proposed form of DCT. This filter can identify noise, compact energy, and it has lower complexity than other filters using its real bases. Furthermore, this model does not require pre-known data on the targeted signal and coherency.

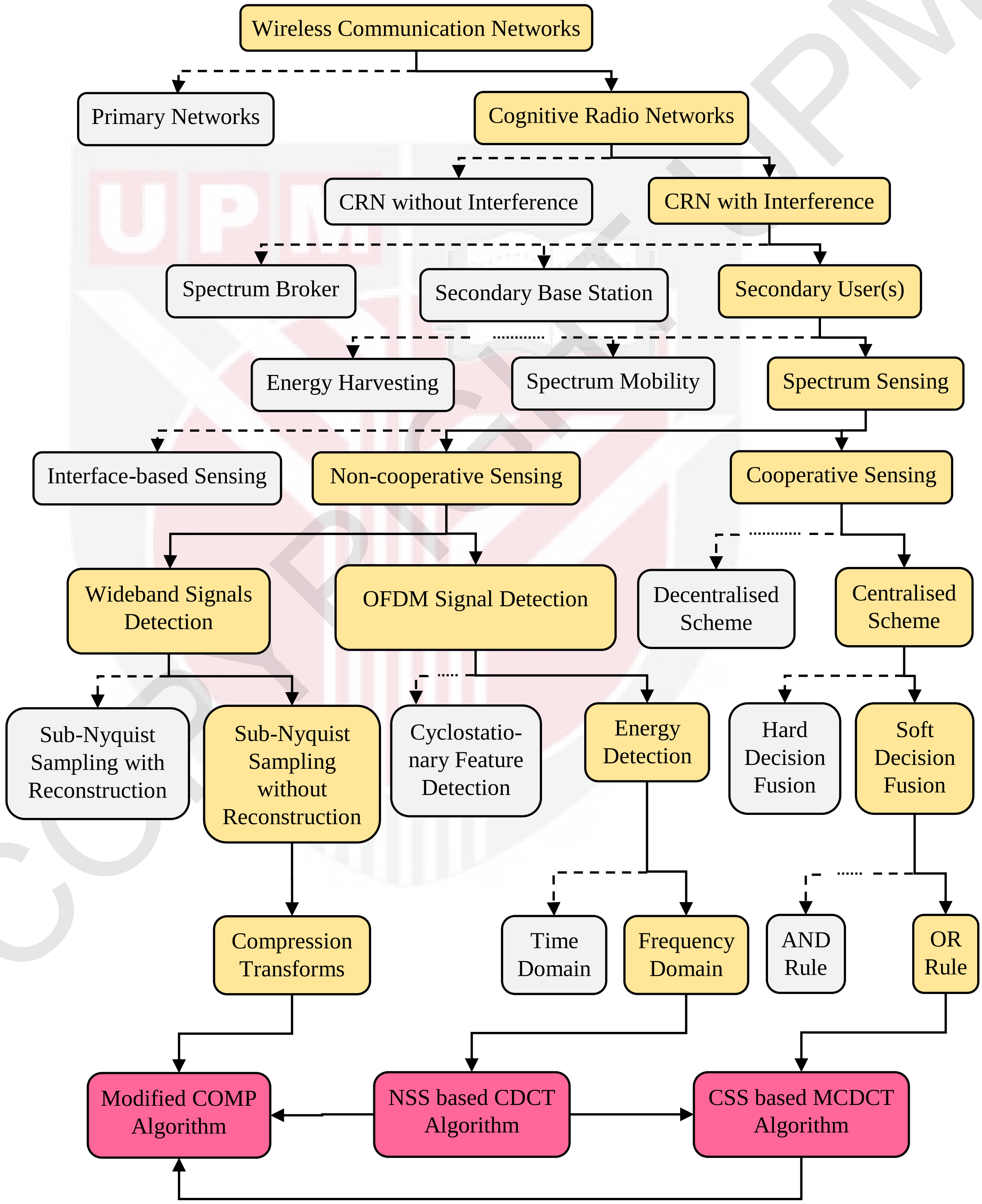

Figure 1.3 : The Scope of the Thesis

The second objective is performed in the chapter 4 by upgrading the NSS algorithm. The proposed CSS algorithm was developed using the multi CDCT (MCDCT) filters and the soft decision fusion (SDF) to sense the same previous types of signals. This algorithm can address problems such as the detection performance, computational complexity, and the limited number of secondary users. More investigations and analyses are depicted in the Chapter 4.

Chapter 5 shows another sensing algorithm that is required for sensing the OFDM signals using COMPSS technique. This chapter is divided into two main parts: the COMPSS algorithm and the modified COMPSS algorithm. In the first part, the COMPSS algorithm was derived using the non-recovery matrix form of CDCT (MCDCT). This algorithm has two main models: one for SU and other for centralised cooperative SUs. It will be shown that both models addressed issues such as conserving sensed signal measurement and computational complexity but did not significantly reduce the consumed power.

To significantly meet the challenges of the last issue mentioned above, a modified COMPSS algorithm was developed, and this forms the second part of Chapter 5. This technique was performed using two cascaded transforms: discrete Daubechies wavelet transform (DDWT), followed by MCDCT. It also has two models using non-recovery matrix form for one SU and other for centralised cooperative SUs. To vastly reduce power consumption, DDWT should precede MCDCT in system building.

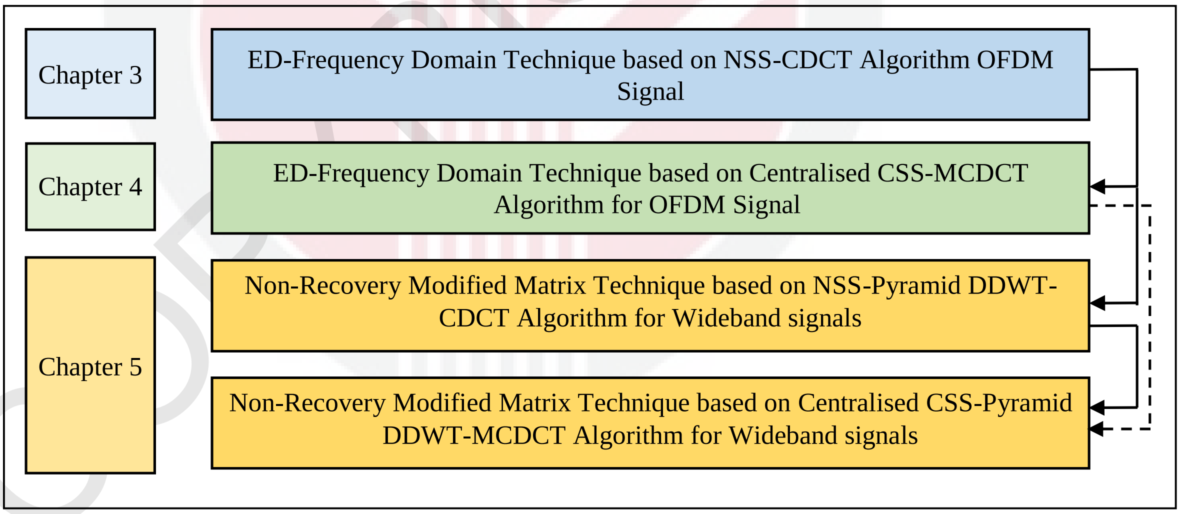

Figure 1.4 : The Research Methodology

In general, both parts have less computational complexity, do not need signal reconstructing, and have incoherence transmitting, reduced consumed power, and high detection performance. Moreover, the OR-rule is used in both stages to achieve the proposed techniques from one secondary user to multi-secondary users. Investigations and analyses are described in detail in Chapter 4.

1.6 Contributions of Thesis

Based on the aforementioned objectives, this thesis presents the following contributions to the existing body of work:

A. Develop a New NSS Technique to Sense OFDM Signal.

The new NSS technique that is developed in Chapter 3 differs in four ways from the traditional ones mentioned in the literature. First, it can differentiate noise from the information signal, while the others could not. Second, it can decrease the SNR wall (i.e., work accurately in low SNR), while the best technique from the literature could do it no smaller than -5dB. Third and fourth, its computational complexity level is lower than others, and its detection performance is better than others. Furthermore, the developed technique does not need coherency transmitting and no pre-known data is required.

B. Develop a New CSS Technique to Sense OFDM Signal.

The new CSS technique which is designed in Chapter 3 is based on trade-offs among detection performance, computational complexity level, and a number of SUs. Other techniques that are cleared in the literature did not address the above factors especially the number of SUs.

C. Design a New COMPSS Technique to Sense Wideband Signals.

In Chapter 4, the new COMPSS technique is designed to counter specifications which were not efficiently addressed in other surveyed techniques. The specifications are better detection performance and easier computational complexity. Moreover, the new COMPSS technique can be applied to single or multi-secondary users in a CRN.

D. Design a Modified COMPSS Technique to Significantly Decrease the Power Consumption.

The modified COMPSS technique which is designed in Chapter 4 significantly reduces the power consumption in receiver front ends during the sensing process. Thus, the proposed technique makes the hardware of receiver front ends cheaper since its computational model is acceptable when compared to other surveyed techniques. In addition, it can be applied to single and multi-secondary users in a CRN.

E. Analytical Models to Obtain the Better Detection Performance of Designed Techniques

All the above techniques were obtained analytically in Chapter 3. They were used to compare the overall performance of the proposed NSS and CSS techniques against the traditional SS techniques. The analytical models contain the SNR wall, computational complexity, detection performance, and noise identification. In a similar manner, another comparison in Chapter 4 was made for the proposed COMPSS technique.

1.7 Thesis Organisation

This chapter gave a brief introduction and outlined the problem statement and the main objectives of the thesis as well as the scope of the study and its significance. The rest of this thesis is organised as follows:

Chapter 2 presents the current SS techniques that are used in a CRN for one-SU and multi-SU schemes, and current COMPSS techniques that are used to sense wideband signals. Related studies on the SS techniques (rather than COMPSS techniques) that work in various wireless networks are also reviewed and analysed. Two comparisons are made to analyse these related studies: the first is for the ED-based SS techniques, and the second is for the COMPSS techniques. Finally, a solution for the ED-based SS, COMPSS, and modified COMPSS are introduced to solve the ED-based SS and COMPSS techniques issues.

In Chapter 3 and 4, the proposed ED-based SS scenarios of NSS and CSS for OFDM signal are systematically modelled and formulated based on CDCT and CDCT + OR-rule, respectively. Next, the chapter outlines the steps taken to achieve the first and second objectives of this study, and the results are presented. Then, a system level simulation for each of the above models is designed to validate the proposed techniques. After that, the results of the analytical and system simulations are shown graphically and numerically. Finally, a comparison is made between the proposed work and benchmark studies.

Chapter 5 begins with the derived expressions of the proposed COMPSS scenarios of NSS and CSS for wideband signals and the built system models which are based on NSS and CSS These expressions are derived from the proposed system which is explained in Chapter Three. Then, the chapter presents the results that relate to the achievement of the third objective. Next, the modified COMPSS is performed based on DDWT + MCDCT and DDWT + MCDCT + OR-rule for NSS and CSS, respectively, and the results are presented. After that, a system level simulation for each of the above models is designed to validate the proposed techniques. Then, the results of the analytical and system simulations are shown graphically and numerically. Finally, a comparison is made between the proposed work and related works.

In Chapter 6, the thesis summary, its conclusions, and various suggestions for further studies are introduced.

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LIST OF PUBLICATIONS

International Journals and Conferences

Salman, Emad Hmood, Nor Kamariah Noordin, Shaiful Jahari Hashim, Fazirulhisyam Hashim, and Chee Kyun Ng. "An overview of spectrum sensing techniques for cognitive LTE and LTE-A radio systems." *Telecommunication Systems* 65, no. 2 (2017): 215-228. Impact Factor JCR-2017: 1.542.

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Awards

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