



بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ



Sudan University of Science and Technology

College of Graduate Studies

**Performance of Interchangeable Spectrum
Sensing Scheduling Algorithm in Multiband
Environment**

**آداء خوارزمية جدولة استشعار طيف متبادلة في بيئة متعددة
النطاقات**

A Thesis Submitted in Partial Fulfillment of the Requirements for the
Degree of M.Sc.in Electronic Engineering (Communications Engineering)

Prepared by:

Deena Abdallah Ahmed Abbas Heiba

Supervised by:

Dr.Mohamed Hussein Mohamed

March 2017

الآية

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

"قُلْ لَوْ كَانَ الْبَحْرُ مِدَاداً لِكَلِمَاتِ رَبِّي لَنَفَذَ
الْبَحْرُ قَبْلَ أَنْ تَنْفَذَ كَلِمَاتُ رَبِّي وَلَوْ جِئْنَا بِمِثْلِهِ
مَدَداً"

صدق الله العظيم

سوره الكهف: الآية 109

Dedication

There are a number of wonderful people who have inspired us in life, and to which I would like to dedicate this thesis to and in their memory .To my parents how inspire me , and to my family and friends.

ACKNOWLEDGEMENT

First of all, I thank god (ALLAH) for giving me the endurance and perseverance to complete this work.

I am truly indebted and thankful to my supervisor Dr. Mohamed Hussein for his suggestions, criticism and guidance throughout the thesis work.

I could not complete this work without the continuous support of my family; I would like to give special thanks to my family.

I am very thankful to Ali Omer for his constructive comments and supporting in pursuing this work.

ABSTRACT

Cognitive radio is one of the most important approaches to utilize the radio frequency spectrum efficiently. Cognitive Radio is a promising technology that is potentially will play an essential role of communications in the future. This technology witnesses a rapid growth in the past few years due to the solutions it provides. One of the main issues regarding cognitive radio technology is spectrum-sensing methods. Even though many research efforts were dedicated to improve sensing efficiency, it is considered in the early stages. The novel Interchangeable Spectrum Sensing Scheduling algorithm attempted to improve the sensing efficiency through a cooperative sensing scheme. This thesis conducts thoroughway prototype to evaluate the performance this algorithm. MATLAB platform was used to simulate the scheduling operation and channel status on different number of band and evaluated in terms of the contribution to reduce the interference with the primary user as well as the opportunity losses .Also Calculated the noise influence on probability of false alarm at noisy environment with specific SNR. In this regards the performance of spectrum sensing was improved when using the different number of bands and different value of SNR.

المستخلص

الشبكات الراديوية الذكية هي إحدى أهم المداخل لإستخدام الطيف الترددي بصورة مثلى ,الشبكات الراديوية الذكية هي تقنية واعدة ستلعب دوراً أساسياً في مجال الإتصالات في المستقبل. هذه التقنية شهدت نمواً متسارعاً في السنوات القليلة الماضية نظراً للحلول التي تقدمها. إحدى القضايا الرئيسية المعتبرة لتقنية الشبكات الراديوية الذكية هي طرق إستشعار الطيف. بالرغم من أن الكثير من جهود البحث كُرسَتْ لتحسين كفاءة إستشعار الطيف إلا أن طرق الإستشعار تعتبر في مراحلها الأولية من حيث الكفاءة. خوارزمية جدولة إستشعار الطيف التبادلية المبتكرة حاولت تحسين كفاءة إستشعار الطيف من خلال طرق الإستشعار التعاونية. هذه الأطروحة تجري نموذجاً مصغراً لتقييم الخوارزمية أعلاه. أستخدم برنامج الماتلاب لمحاكاة عملية الجدولة و حالة القناة عند إستخدام عدد من النطاقات و تقييم المساهمة لتقليل من التداخل مع المستخدم الأولي بالإضافة إلي فقدان الفرصة.وأيضا حساب تأثير الضوضاء علي إحتمالية الإنذار الخاطئ في بيئة ضوضائية بإستخدام قيمة محددة لنسبة الإشارة إلي الضوضاء . وفي هذا الصدد إن أداء إستشعار الطيف تحسن عندما أستخدم عدد من النطاقات و قيم مختلفة لنسبة الإشارة الي الضوضاء .

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List of Abbreviations

BS	Base Station
CPE	Customer Premises Equipment
CR	Cognitive Radio
CR-CPE	Cognitive Radio Customer Premises Equipment
CRN	Cognitive Radio Network
GPS	Global Positioning System
GSM	Global System Mobile
IBSHO	Inter-Band Soft Handover
ISP	Internet Server Provider
ISSS	Interchangeable Spectrum Sensing Scheduling
LO	Local Oscillator
MF	Matched Filter
MPME	Multiband Primary Network Environment
PC	Probability of collision
Pd	Probability of Detection
Pf	Probability of False Alarm
Ps	Probability of successful Transmission
PU	Primary Users
QOS	Quality Of Service
SDR	Software Define Radio
SNR	Signal to Noise Ratio

SU

Secondary Users

UWB

Ultra-Wide Band

WRAN

Wireless Regional Area Network

List of symbols

$y(n)$	Received signal
$s(n)$	Detected signal
$w(n)$	Additive white Gaussian noise
H	Channel response
V_T, λ_E	Energy detection Threshold
σ_N	Noise power

Chapter One

Introduction

1.1 Preface

Cognitive radio is one of the most important approaches to utilize the radio frequency spectrum efficiently. Traditionally, regulation authorities allocate fixed frequency band to each licensed user, thus ensure minimum amount of interference. However, as the demand for more frequencies increases, the available wireless bands are almost occupied, as an example in United States National Telecommunication and Information Administration reported that the frequency bands are entirely occupied [1].

Now, it is convenient to define the primary and secondary users, “primary users (PU) can be defined as the users who have higher priority or legacy rights on the usage of a specific part of the spectrum. On the other hand, secondary users, which have lower priority, exploit this spectrum in such a way that they do not cause interference to PU. Therefore, secondary users need to have cognitive radio capabilities, such as sensing the spectrum reliably to check whether a primary user is using it and to change the radio parameters to exploit the unused part of the spectrum” [2].

Cognitive Radio (CR) was recognized as an enabling technology to mitigate the abused scarce radio frequency spectrum dilemma; hence dynamic spectrum access is proposed to share the available spectrum through opportunistic usage of the frequency bands by secondary operators without interfering with the primary networks.

When CR Networks (CRN) installed it will enable the secondary networks to perform the following tasks;

- Spectrum Sensing; determine instantaneous available spectrum portions and detect the presence of primary users (PU).

- Spectrum Management; coordinate the assignment of radio channels to its node from the available channel list, and
- Mobility Management; vacate the channel when a licensed user is detected and handoff to another available channel.

This technology offers the opportunity to optimize the spectrum access, assist in preventing interference and, adapt instant spectrum slot available from the unutilized spectrum pool. Since CRN is responsible for detecting the existence of the primary user transmission, while no add-ons protocols will installed on the primary networks, the accuracy of spectrum sensing is the key challenge in deploying CRN technology in order to avoiding harmful interference to the primary networks. This necessitates support by the access layer of the CRN architecture via intelligent algorithms for sensing and scheduling [3].

1.2 Problem Statement

Spectrum sensing in CRN depends on two metrics, probability of detection (P_d) and probability of false alarm (P_f). Some techniques are proposed in order to improve the sensing performance metrics, such as the interchangeable spectrum sensing scheduling algorithm (ISSS). The algorithm improved the probability of detection, albeit the false alarm probability increased, which lead to degradation of the cognitive system performance. The simulation seeks optimum sensing performance.

1.3 Proposed solution

To get an optimum value of the probability of false alarm which was obtained by using ISSS algorithm, different scenarios should evaluate under different circumstances (different signal to noise ratio (SNR) and band occupancy) to measure the impacts on the probability of false alarm, then a comparison between the different bands system's performance must be done to get the optimum number of band that must be used at the system.

1.4 Objectives

The objectives of this thesis are to;

- Study cognitive radio.
- Analyze and simulate ISSS Algorithm.
- Evaluate the performance of ISSS algorithm of cognitive radio system.
- Increasing the performance of the cognitive system, by decreasing the probability of false alarm.

1.5 Methodology

A MATLAB code will be used to simulate the channels status depending on the activity of the primary user then deploys a systems that use different number of bands and calculate their contribution at increasing the detection probability over the single band system. The system is use at noisy environment with specific SNR to calculate the noise influence on the false alarm probability of each system.

1.6 Thesis outlines

The rest of this thesis is organized as follow:

Chapter two: provide a literature review of general cognitive radio history beside a spectrum sensing overview. **Chapter three:** layout the methodology of using ISSS algorithm, **Chapter four:** presents the simulation and discuss the results and **Chapter five:** concludes the thesis and provides recommendations of the future work.

Chapter Two

Literature Review

2.1 Introduction

Cognitive radio, from the name it can denote that this device can understand or know if the radio channel is free or not. It means to use the spectrum resources when it's not allocated by owner user (free) to sufficient utilization.

Cognitive Radio is an option to utilize non-used parts of the spectrum that actually are assigned to what is known as “primary user”. In other words, cognitive radio is proposed to solve the unbalance between spectrum scarcity and underutilization of the spectrum.

The Federal Communications Commission (FCC) defines the Cognitive radio as a radio that can change its transmitter parameters based on interaction with the environment in which it operates. Figure 2.1 show the simple idea of cognitive radio network [3].

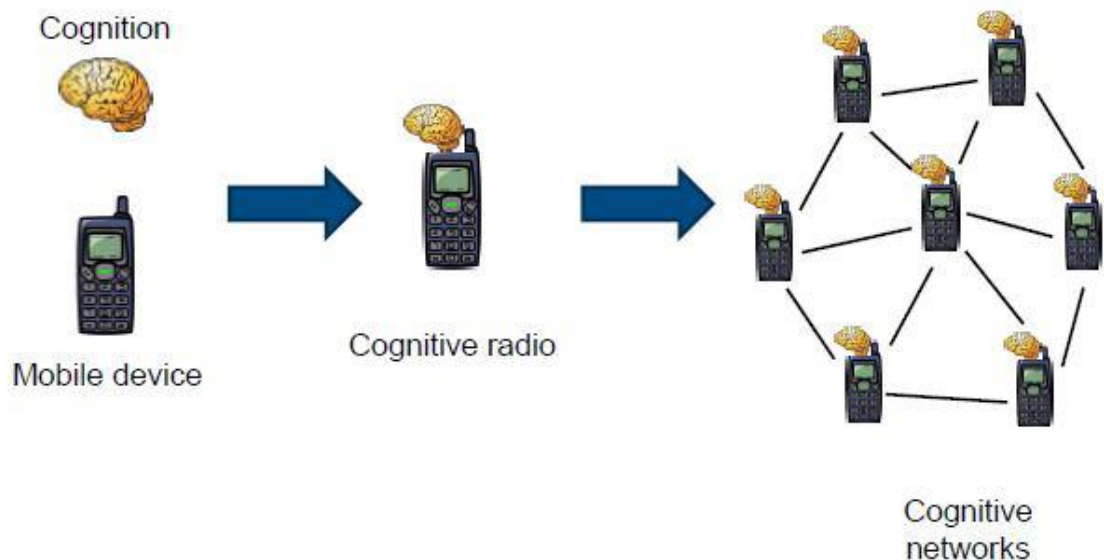


Figure 2.1: Cognition, Cognitive radio and Cognitive networks

2.2 Related work

First of all Cognitive radio was proposed in 1999[4], by J. Mitola and G. Q. Maguire as a promising technology to fully exploit the under-utilized spectrum. And in 2000 J. Mitola also discussed An Integrated Agent Architecture for Software Defined Radio in cognitive radio [5].

The cognitive radio then faced several challenges such as; multipath fading, shadowing and hidden node problem where a few sensing methods were proposed. In 2005 A. Sahai et al proposed the energy detection method as a spectrum sensing technique [6].

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Next in 2007 H. Arslanwrite a book in cognitive radio this book is aimed to discuss the cognitive radio, software defined radio (SDR), and adaptive radio concepts from several aspects [8]. In 2007 also Y. Zeng, Y. C. Liang presented new spectrum sensing technique in cognitive radio [9].

According to Yücek and et al in 2009 Spectrum sensing is the task of gaining awareness about the spectrum usage and existence of primary users in a geographical area. This awareness can be obtained by using geolocation and database [2].

The classification depends on the need of spectrum sensing as stated by Subhedar and et al in 2011 are classify into two categories spectrum sensing for spectrum opportunities its included primary transmitter detection and cooperative collaborative detection. The other category is spectrum sensing for interference detection that includes Interference temperature detection and Primary receiver detection[10].

The worldwide first application of CR networks in unlicensed television broadcast bands is IEEE 802.22 wireless regional area network (Subramaniam and et al in 2014) [11].

The performance of the detection algorithm can be summarized with two probabilities: probability of detection (P_d) and probability of false alarm (P_f) [2]. P_d is the probability of detecting a signal on the considered frequency when it truly is present. As demonstrated by Salih and et al in 2013, cooperative detection is more accurate in terms of detecting the primary transmitter activities; this scheme is obviously increase the detection probability On the other hand, this scheme also increases the false alarm probability[12].

2.3 Concept of Cognitive Radio Technology

Cognitive radio networks consist of three elements (Xiao and Hu 2008) [3]:

1. The cognitive radio (CR) user, the CR user do not have a licenses band, this user use the band of the primary user opportunistically when the band is free. Sensing task is applied internally on the CR user. However they do not make a decision on the spectrum band availability, they only report the sensing results to a base station.

2. The CR base station, the CR base station is a fixed infrastructure in a CR network that manages and controls the spectrum. CR users report their sensing result to the CR base station in order to make a decision on the spectrum availability. Furthermore CR base station provides synchronization in the sensing operations among the CR users.
3. Spectrum broker, Spectrum broker is a centralized entity that allows CR networks to share the available spectrum resources. It is not directly responsible for the sensing operation, it only manage the available spectrum resources according to the sensing information collected by each network.

The key enabling technologies of CR networks are the cognitive radio techniques that provide the capability to share the spectrum in an opportunistic manner. Formally, a CR is defined as a radio that can change its transmitter parameters based on interaction with its environment. From this definition, two main characteristics of cognitive radio can be defined;

- Cognitive Capability: Through real-time interaction with the radio environment, the portions of the spectrum that are unused at a specific time or location can be identified. As shown in Figure 2.2, CR enables the usage of temporally unused spectrum, referred to as spectrum hole or white space.

Consequently, the best spectrum can be selected, shared with other users, and exploited without interference with the licensed user.

- Cognitive Re-configurability: A CR can be programmed to transmit and receive on a variety of frequencies, and use different access technologies supported by its hardware design. Through this capability,

the best spectrum band and the most appropriate operating parameters can be selected and reconfigured.

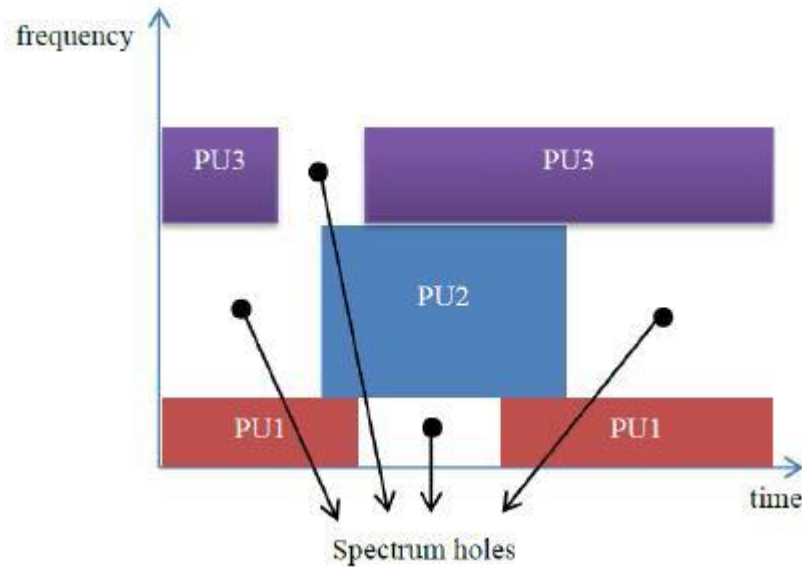


Figure 2.2: Cognitive Radio Spectrum Holes.

More specifically, the cognitive radio technology will enable the users to:

- 1- Spectrum Sensing: determine which portions of the spectrum are available and detect the presence of licensed users when a user operates in a licensed band.
- 2- Spectrum Management: selects the best available channel.
- 3- Spectrum Mobility: vacate the channel when a licensed user is detected.
- 4-Spectrum Sharing: coordinate access to this channel with other users.

2.4 Cognitive Radio Network Architecture

The cognitive radio network can be deployed in network-centric, distributed, ad hoc, and mesh architectures, and serve the needs of both licensed and unlicensed applications.

The basic components of CRNs are mobile station (MS), base station/access point (BSs/APs) and backbone/core networks. These three basic components compose three kinds of network architectures in the CRNs: Infrastructure, Ad-hoc and Mesh architectures, which are introduced as follows.

2.4.1 Infrastructure Architecture

In the Infrastructure architecture, a MS can only access a BS/AP in the one hop manner. MSs under the transmission range of the same BS/AP shall communicate with each other through the BS/AP. Communications between different cells are routed through backbone/core networks. The BS/AP may be able to execute one or multiple communication standards/protocols to fulfill different demands from MSs. A cognitive radio terminal can also access different kinds of communication systems through their BS or AP as shown in Figure 2.3.

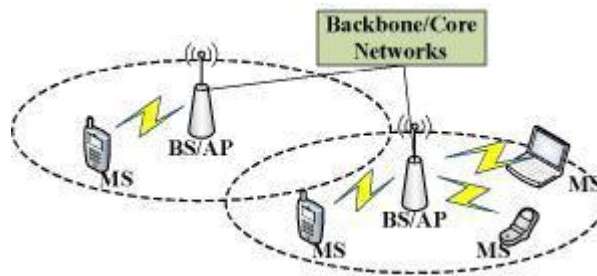


Figure 2.3: infrastructure architecture.

2.4.2 Ad-hoc Architecture

There is no infrastructure support (or defined) in ad-hoc architecture. If an MS recognizes that there are some other MS nearby and are connectable through certain communication standards/protocols, they can set up a link and thus form an ad hoc network. Note that links between nodes may be set

up by different communication technology. Two cognitive radio terminals can either communicate with each other by using existing communication protocols (e.g. WiFi, Bluetooth) or dynamically using spectrum holes as shown in Figure 2.4.

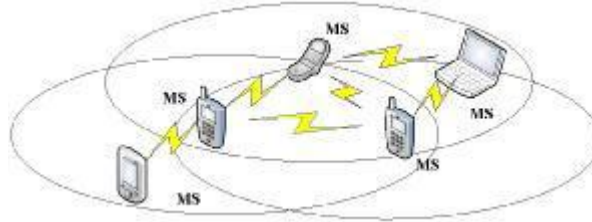


Figure 2.4: Mesh architecture.

2.5 Spectrum sensing overview

Radio spectrum is not efficiently used, mainly due to the prevailing rigid frequency allocation policy. Only some bands of the spectrum - such as those bands used by cellular base stations - are heavily used. Many bands are not used at all or are used only part of the time. Radios using cognitive radio technology are aware of their frequency environment.

Spectrum sensing classified as; primary transmitter detection, interference based detection and cooperative detection.

2.5.1 Primary Transmitter Detection

Transmitter detection approach is based on the detection of the weak signal from a primary transmitter through the local observations of cognitive radio users. Basic hypothesis model for transmitter detection can be defined as in equation 2.1

$$x(t) = \begin{cases} n(t)H_0 \\ h s(t)H_1 \end{cases} \quad 2.1$$

Where $x(t)$ is the signal received by the cognitive radio user, $s(t)$ is the transmitted signal of the primary user, $n(t)$ is the AWGN and h is the amplitude gain of the channel. H_0 is a null hypothesis, which states that there is no licensed user signal in a certain spectrum band. On the other hand, H_1 is an alternative hypothesis, which indicates that there exists some licensed user signal [13].

There are two detection techniques that involve the transmitter detection and these are; Matched Filter Detection and Energy Detection.

2.5.1.1 Energy Detection

Energy detection is a spectrum sensing method that detects the presence/absence of a signal just by measuring the received signal power.

Energy Detection (ED) is the most popular sensing technique in cooperative sensing.

Energy detection technique are also called BLIND SIGNAL DETECTION because it ignores the structure of the signal and estimates the presence of the signal by comparing the energy received with a known threshold derived from the statistics of the noise [14].

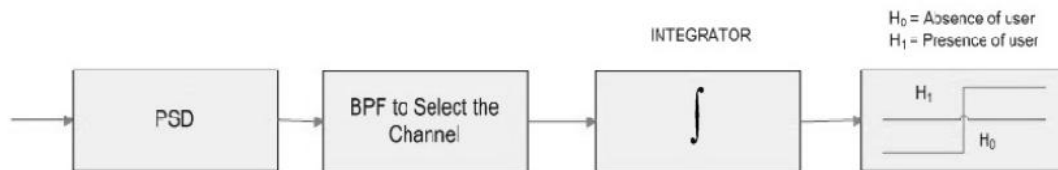


Figure 2.5: Energy Detection block diagram

The block diagram for the energy detection technique is shown in the Figure 2.5. In this method, signal is passed through band pass filter of the

bandwidth W and is integrated over time interval. The output from the integrator block is then compared to a predefined threshold. This comparison is used to discover the existence of absence of the primary user. The threshold value can set to be fixed or variable based on the channel conditions.

Let us assume that the received signal has the following simple form

$$y(n)=s(n)+w(n) \quad (2.2)$$

Where $s(n)$ is the signal to be detected, $w(n)$ is the additive white Gaussian noise (AWGN) sample, and n is the sample index. Note that $s(n) = 0$ when there is no transmission by primary user. The decision metric for the energy detector can be written as

$$M = \sum_{n=0}^N |y(n)|^2 \quad (2.3)$$

Where N present the size of the observation vector. The decision on the occupancy of a band can be obtained by comparing the decision metric M against a fixed threshold λ_E . This is equivalent to distinguishing between the following two hypotheses:

$$y(n) = w(n) \dots \dots \dots H_0 \quad (2.4)$$

$$y(n) = h * s(n) + w(n) \dots \dots \dots H_1 \quad (2.5)$$

2.5.1.2 Matched Filter

The matched filter is the linear optimal filter used for coherent signal detection to maximize the signal-to-noise ratio (SNR) in the presence of additive stochastic noise.

This detection method is known as an optimal detector in stationary Gaussian noise. However, the matched filter necessitates not only a prior knowledge of the characteristics of the Primary User signal but also the synchronization between the Primary User transmitter and the Cognitive Radio user [5].

Matched filter operation is equivalent to correlation in which the unknown signal is convolved with the filter whose impulse response is the mirror and time shifted version of a reference signal. The operation of matched filter detection is expressed as:

$$Y[n] = \sum_{k=-\infty}^{\infty} h[n - k].x[k] \quad (2.6)$$

Where ‘x’ is the unknown signal (vector) and is convolved with the ‘h’, the impulse response of matched filter that is matched to the reference signal for maximizing the SNR. Detection by using matched filter is useful only in cases where the information from the primary users is known to the cognitive users [15].

2.5.2 Interference Based Detection

Interference is typically regulated in a transmitter-centric way, which means interference can be controlled at the transmitter through the radiated power, the out-of-band emissions and location of individual transmitters. However, interference actually takes place at the receivers.

However, there exist some limitations in measuring the interference temperature. The interference is defined as the expected fraction of primary users with service disrupted by the cognitive radio operations. This method considers factors such as the type of unlicensed signal modulation, antennas,

ability to detect active licensed channels, power control, and activity levels of the licensed and unlicensed users [5].

2.5.2.1 Primary Receiver Detection

In general, primary receiver emits the local oscillator (LO) leakage power from its RF front end while receiving the data from primary transmitter. It has been suggested as a method to detect primary user by mounting a low cost sensor node close to a primary user's receiver in order to detect the LO leakage power emitted by the RF front end of the primary user's receiver which are within the communication range of CR system users. The local sensor then reports the sensed information to the CR users so that they can identify the spectrum occupancy status. We note that this method can also be used to identify the spectrum opportunities to operate CR users in spectrum overlay [10].

2.5.2.2 Interference Temperature Management

The basic idea behind the interference temperature management is to determine an upper interference limit for given frequency band in specific geographic location so the CR users are not allowed to cause harmful interference while using the specific band in specific area. CR user transmitters control their interference by limiting their transmission power based on their locations with respect to primary receivers. This method basically concentrates on measuring interference at the receiver (Thanayankizil 2008) [16].

However, this model describes the interference disrupted by a single cognitive radio user and does not consider the effect of multiple cognitive radio users. In addition, if cognitive radio users are unaware of the location

of the nearby primary users, the actual interference cannot be measured using this method. A direct receiver detection method is presented, where the local oscillator (LO) leakage power emitted by the RF front-end of the primary receiver is exploited for the detection of primary receivers. In order to detect the LO leakage power, low-cost sensor nodes can be mounted close to the primary receivers. The sensor nodes detect the leakage LO power to determine the channel used by the primary receiver and this information is used by the unlicensed users to determine the operation spectrum [17].

2.5.3 Cooperative spectrum sensing

In the CR networks there is a lack of interaction between PU and SU. Transmitter detection based sensing merely detect weak transmitter signals. Hence, the primary transmitter detection techniques cannot avoid interference with the primary signal because the lack of information, also the hidden node and shadowing problems can result in inaccurate sensing information causing interference as shown in figure 2.6. Therefore sensing information from other CR users is needed to obtain better sensing accuracy. This is referred to as cooperative sensing.

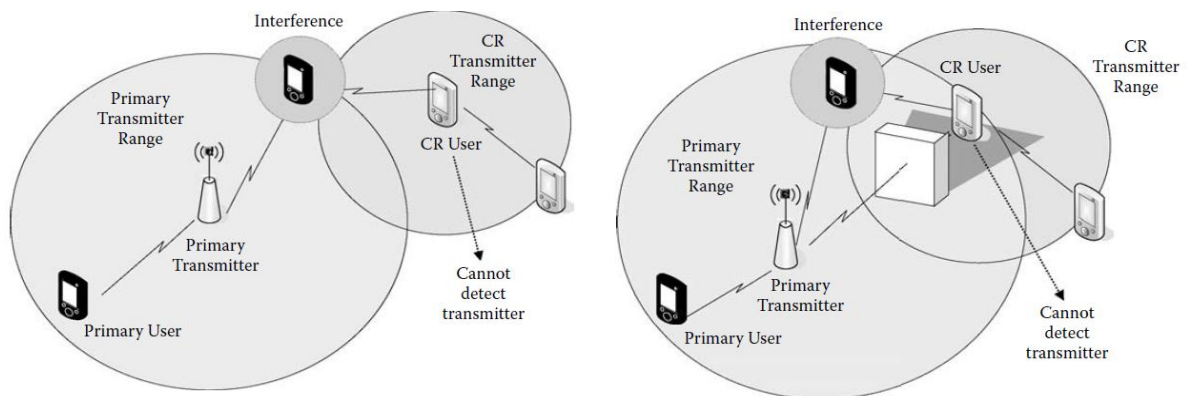


Figure 2.6: Hidden node and shadowing problems [10]

The cooperative spectrum sensing can be classified into three categories based on how they share sensing information between them: centralized, distributed and relay-assisted. These three types are illustrated in figure 2.7.

In centralized spectrum sensing technique, a central identity called base station transceiver control the three steps process of sensing:

- 1- The base transceiver chooses the frequency bands and instructs all the CR users to perform sensing.
- 2- The CR users report the sensing results to the base transceiver.
- 3- The base transceiver compares the results to determine the presence of PU and send the decision to all cooperating CR users.

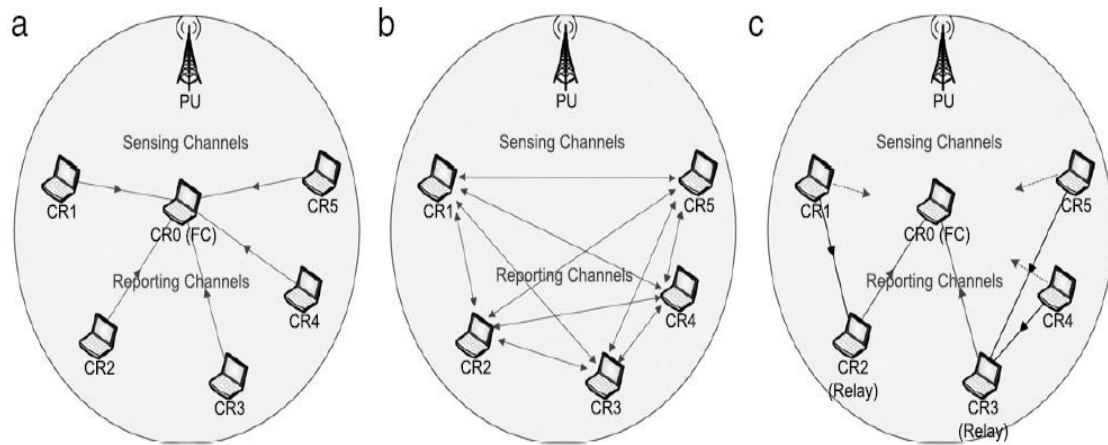


Figure 2.7: Cooperative sensing techniques: a) centralized b) distributed
c) relay-assisted [15]

Centralized schemes can be further classified according to their level of cooperation as: Partially cooperative where network nodes cooperate only in sensing the channel. CR users independently detect the channel and inform the base transceiver which then notifies all the CR users; and totally

cooperative Schemes where nodes cooperate in relaying each other are information in addition to cooperatively sensing the channel [10].

For reporting sensing data, two major control channel requirements must be satisfied in cooperative sensing: bandwidth, reliability [15].

2.5.4 Sensing performance

The performance of the detection algorithm can be summarized with two probabilities: probability of detection P_d and probability of false alarm P_f [10]. P_d is the probability of detecting a signal on the considered frequency when it truly is present. Thus, a large detection probability is desired. It can be formulated a

$$P_d = \Pr (M > \lambda_e \quad H1) \quad (2.7)$$

P_f is the probability that the test incorrectly decides that the considered frequency is occupied when it actually is not, and it can be written as

$$P_f = \Pr (M > \lambda_e \quad H0) \quad (2.8)$$

P_f should be kept as small as possible in order to prevent underutilization of transmission opportunities. The decision threshold λ_E can be selected for finding an optimum balance between P_d and P_f . However, this requires knowledge of noise and detected signal powers. The noise power can be estimated, but the signal power is difficult to estimate as it changes depending on ongoing transmission characteristics and the distance between the cognitive radio and primary user. In practice, the threshold is chosen to obtain a certain false alarm rate. Hence, knowledge of noise variance is sufficient for selection of a threshold.

As demonstrated in (Salih and others 2013) [12], cooperative detection is more accurate in terms of detecting the primary transmitter activities; this scheme is obviously increase the detection probability obtained by

$$P_d^c = 1 - (1 - P_d)^N \quad (2.9)$$

Where N is the number of cooperative CR-CPEs. On the other hand, this scheme also increases the false alarm probability as follows;

$$P_f^c = 1 - (1 - P_d)^N \quad (2.10)$$

Chapter Three

Methodology

3.1 Introduction

In the previous chapters, a brief overview of the cognitive radio literature is presented. On the other hand, in this chapter, the ISSS algorithm is explained and the evaluation parameters are demonstrated.

In practical implementations of opportunistic spectrum access, the user needs to exploit multiple spectrum bands to mitigate the fluctuations in a single band operation. The environment in which the CR network is mounted assumed to be a Multiband Primary Network Environment (MPNE) which have a multiple primary network, each one of these networks have an exclusive right to access its band. In contrast CR network is only serves its customers opportunistically without interference with the licensed operations.

3.2 ISSS Operation

ISSS uses a centralized cooperative sensing technique which has a central base transceiver cover the area of interest and multiple cognitive radio customer premises equipment (CR-CPE) distributed at the system area called CRN clients. Each CRN client has two transceivers, one to communicate data and the other to exchange control signal with the base transceiver. At last, the control channel should be error free to protect control signal and avoid causing interference to the primary users. Therefore, the control channel state is one of the important factors that determine the performance of cognitive radio system.

The transmission time is the key parameter to achieve the maximum benefit from the cognitive radio, however increasing the transmission time will

cause inaccuracy at the sensing results because the sensing time will reduce. ISSS could achieve a high transmission rate without affecting the accuracy of sensing by distributing sensing task between the CR-CPE clients then pass sensing information to the central base transceiver, then it will provide to each CR-CPE client the information it needs using the error free control channel.

The main concept of ISSS is to make each CR-CPE sense its own spectrum also provide sensing information for the other users bands. Figure 3.1 describe the operation of the algorithm in a system has n CR-CPE ,each CPE has a sensing time in which it sense all system bands then start transmission and the next CPE take responsibility of sensing and so on.

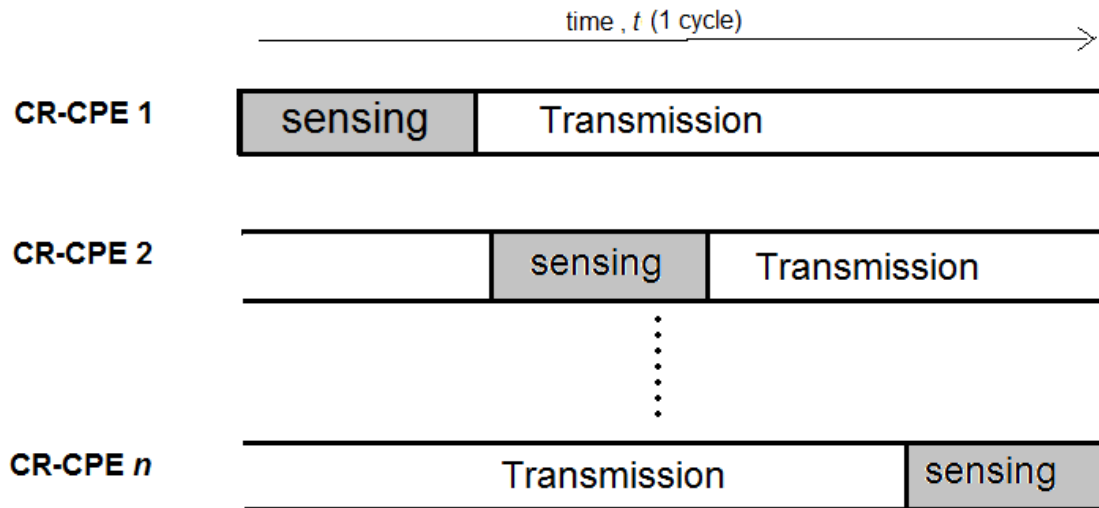


Figure 3.1 ISSS operation

The number of cooperating CPEs is one of the most important factors that determine the performance of the system, the more users cooperate together the more sensing information will be provided and the cycle period will

increase thus the transmission time to each user will increase without affecting the performance of the system.

3.3 Inter-Band Soft Handover

Like in ordinary mobile system, hand over process takes place in ISSS to grantee that no interference occurs to the primary user. The central base transceiver takes the responsibility of performing the handover according to the sensing information. When the primary user appear at the band, the central base transceiver immediately search for a new empty band to assign it to the CR-CPE instead of the busy one using the *inter-band soft handover(IBSHO)*. The handover process should be performed very fast so the secondary user doesn't affect the QOS that primary user needs for its communication [12].

3.4 Performance parameters

The performance of cognitive radio system is determined by many factors including the probability of detection and the probability of false alarm, to get an optimum performance the sensing technique must find a good trade-off between false alarm and miss detection probabilities.

Another way to address the performance of the system from the MAC-layer view point by the throughput of the secondary user and the interference (collision) with the primary users. If the interference with the primary user exceeds the noise floor, it considered as a collision.

To calculate the collision and successful transmission probabilities simple relationship between (P_d, P_f) and (P_s, P_c) is used as follow (Wyglnski 2009) [18].

$$P_s = (1 - P_f) P_r[H0], \quad P_c = (1 - P_d) \quad (3.1)$$

Where:

P_s =probability of successful data transmission

P_f =probability of false alarm

$P_r [H0]$ = probability of idle channel

P_c =probability of collision

P_d =probability of detection

The successful transmission can be defined by two logical conditions: the reception at the secondary receiver being successful and the transmission from the secondary transmitter being harmless (doesn't interfere with primary transmitter). However, it is worth mentioning that in some scenarios the probability of collision is not equal to the probability of miss detection. Furthermore, correctly detected opportunities may lead to failed data transmission, and miss detection may lead to successful data transmission as illustrated in figure 3.2

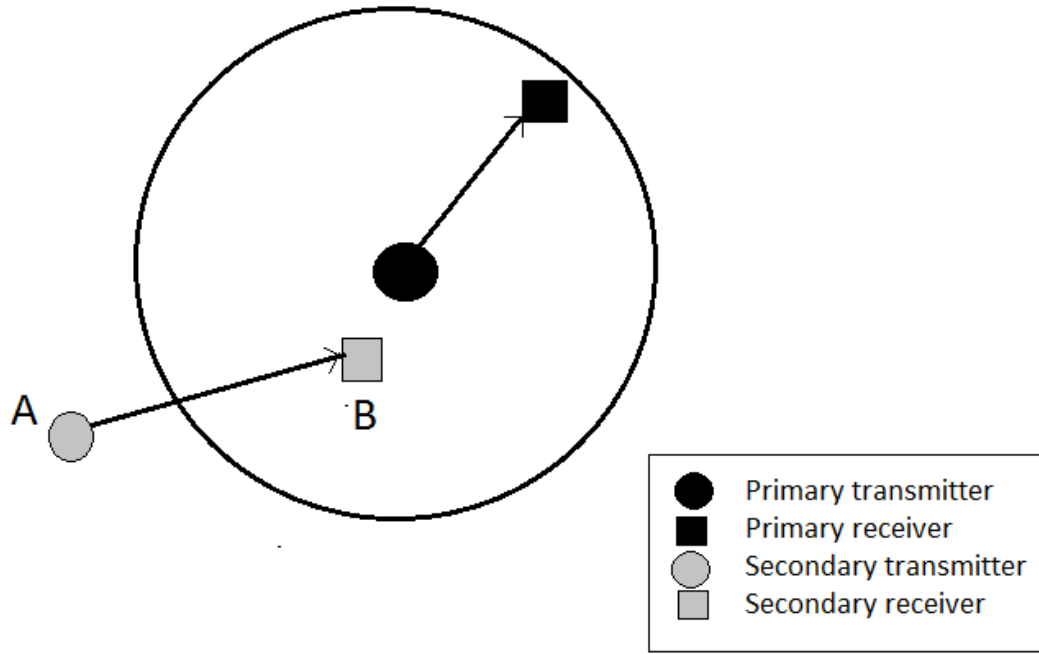


Figure 3.2 Useful miss-detection scenarios

Consider a pair of secondary users A and B seeking to communicate using opportunistic communication with the presence of primary users as shown in figure 3.2. If the receiver B was responsible of sensing process and miss detected the primary user activity the secondary transmitter A will start to transmit to B while the primary users are communicating. However, the secondary transmission will be done successfully without interfering primary user. So although miss detection occurs no collision happened so the probability of collision can be defined as

$$P_c \leq (1 - P_d) \quad (3.2)$$

That mean in some scenarios the miss detection of primary user can be useful by creating a new opportunities. On other hand the false alarm also may be useful by protecting the system from colliding with the primary user as demonstrated in figure 3.3

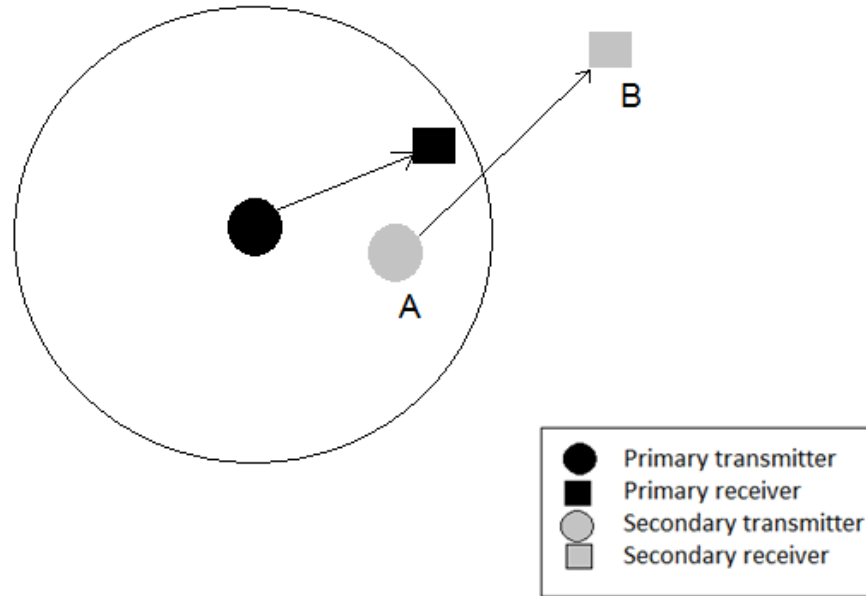


Figure 3.3 Useful false alarm scenarios

If B is responsible from sensing process it can't see the primary transmitter because it is outside of the primary transmitter coverage area so if it decided that the channel is free A will start sending causing a collision at the primary receiver. However if a false alarm occurred at B this will protect the primary users communication from the interference.

3.5 Energy threshold for sensing

As mentioned previously, energy detection sensing is considered simple, since it does not require knowledge about the primary user signal structure.

The main issue explained here, is the selection of the threshold in order to distinguish the spectrum holes in the noisy wireless channel.

The selection of a reasonable threshold is based on the radar detection theory [10].

$$V_T = \sqrt{2\sigma_N^2 \log \frac{1}{P_f}} \quad (3.3)$$

Where V_T is the voltage threshold, and σ_N^2 is the noise power P_f is the probability of false alarm.

Chapter Four

Simulation and Results

4.1 Introduction

In real world, a number of bands in CRN are exploited simultaneously in order to mitigate the fluctuating nature of the opportunistic spectrum access. However, high number of bands may lead to degradation of overall performance due to the overutilization of the spectrum.

In this chapter, the simulation implementation and the results are discussed. MATLAB tools are used to simulate the practical cognitive radio environment of ISSS cooperative sensing as well as evaluation method by calculating the performance parameters of the system.

4.2 Assumptions

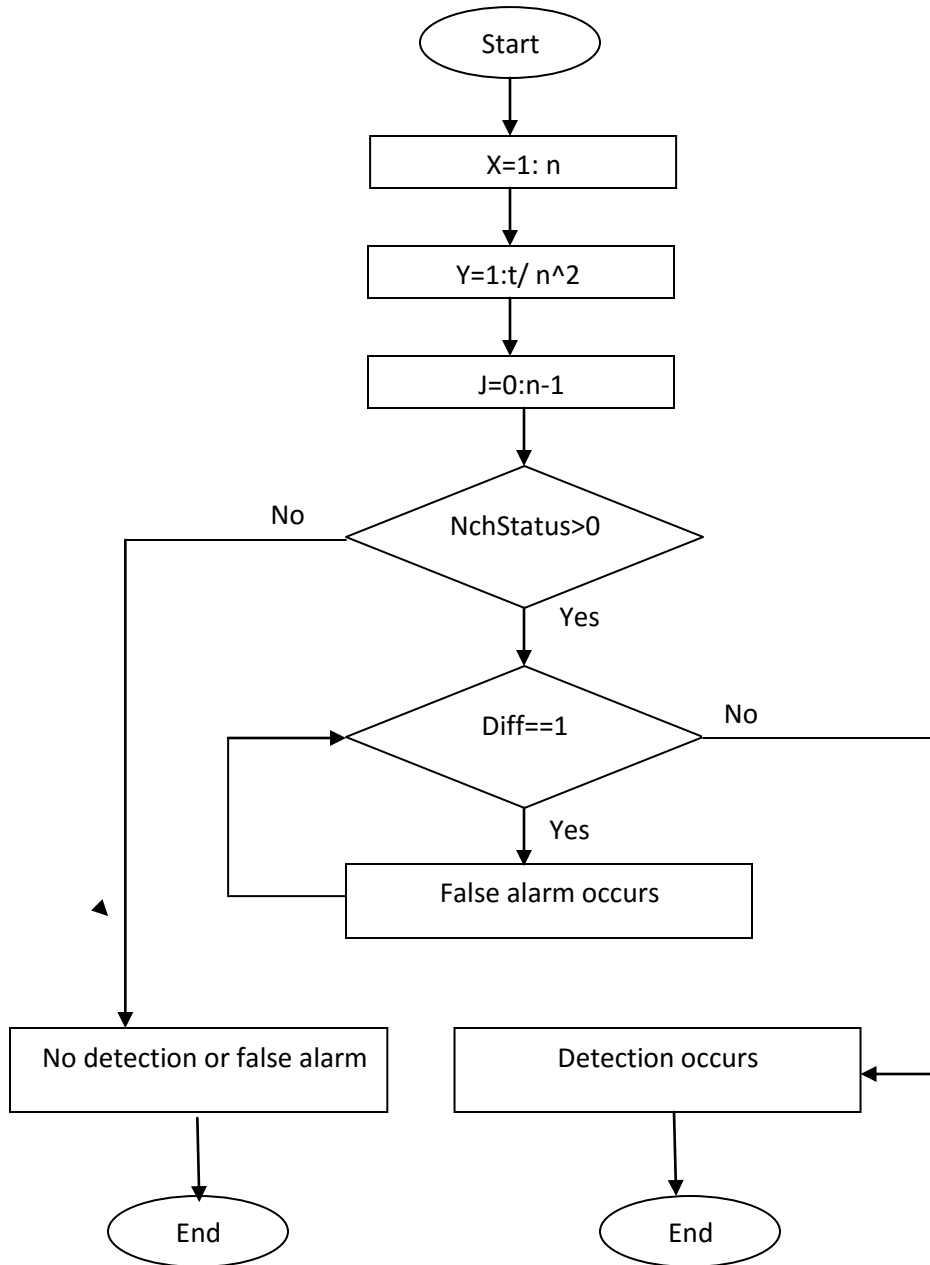
- The system is operating in a geographical location that is already covered by multiple licensed networks such as GSM, WiMAX and TV which referred to as Multiband Primary Network Environment (MPNE).
- The cooperation topology assumed to be centralized architecture with a base station for processing, synchronization and signaling.
- An error free signaling channel providing signaling information with guaranteed availability.

4.3 Sensing in ISSS algorithm

Decision fusion in CRNs aimed to increase the detection probability while keeping the false alarm probability at an acceptable level. Primary network activity has a major effect in the probability of detection as well as the probability of false alarm. The ISSS algorithm suggested that the

probability of detection increases with the primary user activity that is because the primary user operation would meet the sensing time slot at a higher percentage, the reason behind that is discussed later in this chapter. The following Pseudo code simulate sensing task.

ISSS algorithm steps



Sensing Pseudo Code

```

% perform sense task for each band
for x=1:n
    for y=1:t/n^2                                % sensors time slots
        for j=0:n-1
            if NChStatus(x,n^2*y-n^2+x+j*n) > 0
                if diff(x,n^2*y-n^2+x+j*n)==1

                    FA(x)=FA(x)+1;                % False alarm occurs

                    continue;
                end
                sensematrix(x,(y-1)*n^2+1:y*n^2)=j+1;    % Detection occurs
                break
            else
                sensematrix(x,(y-1)*n^2+1:y*n^2)=0;        %No detection nor false alarm
            end
        end
    end
end

```

As demonstrated in the sensing simulation code the channel time is split to frames with length n^2 (where n is the number of bands at the cooperative system). Then sensing process is done by all contributing CPEs to each band at different time slot at the frame. Figure 4.1 show an example of sensing process for a system uses 4 bands (4 CPEs).

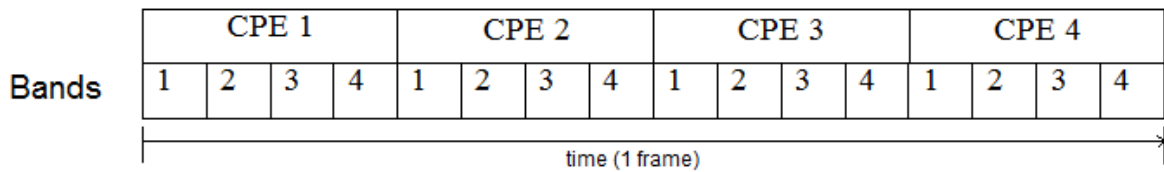


Figure 4.1: Sensing task at 4-bands system

As shown in the figure the sensing is done to each band 4 different time slots at the frame by the 4 CPEs, if the primary signal is detected by any CPE the rest of the frame is considered to be busy and sense matrix will save that the primary signal is detected and determine the CPE that detected it.

4.4 Simulation Results

4.4.1 Probability of detection

Figures 4.2 ,4.3 and 4.4 show the effect of value of interference with applying ISSS algorithm and without applying ISSS algorithm (in two bands, three bands and four bands) using the ISSS algorithm in reducing interference with the primary user.

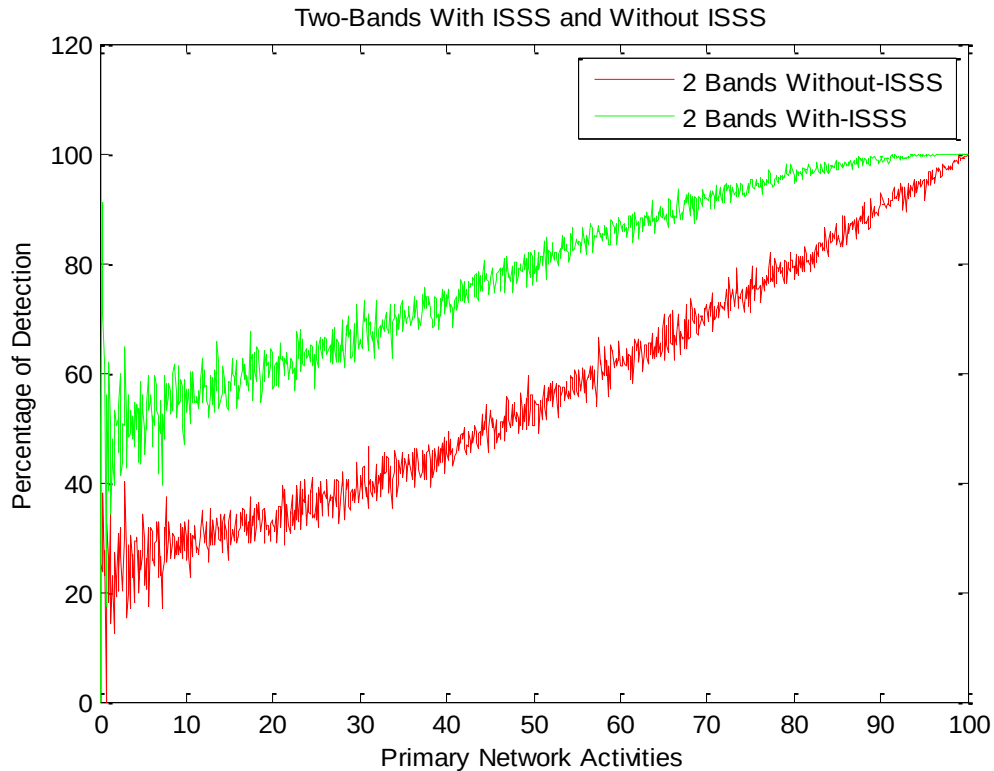


Figure 4.2: ISSS 2-Bands to reduce interference vs. primary network activity

Figure 4.2 shows the percentage of detection when using 2 bands, start with the different value of percentage of detection (its better when using ISSS algorithm) at different primary user activity.

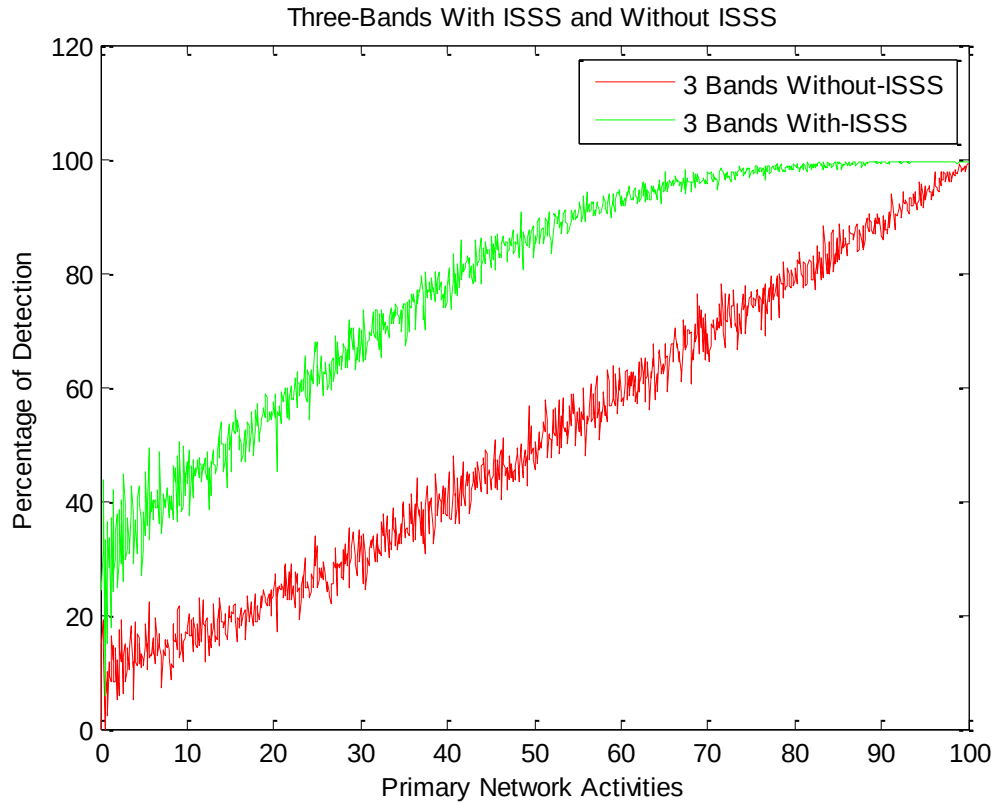


Figure 4.3: ISSS 3-Bands to reduce interference vs. primary network activity

Figure 4.3 shows the percentage of detection when using 3 bands, start with the different value of percentage of detection (its better when using ISSS algorithm) at different primary user activity.

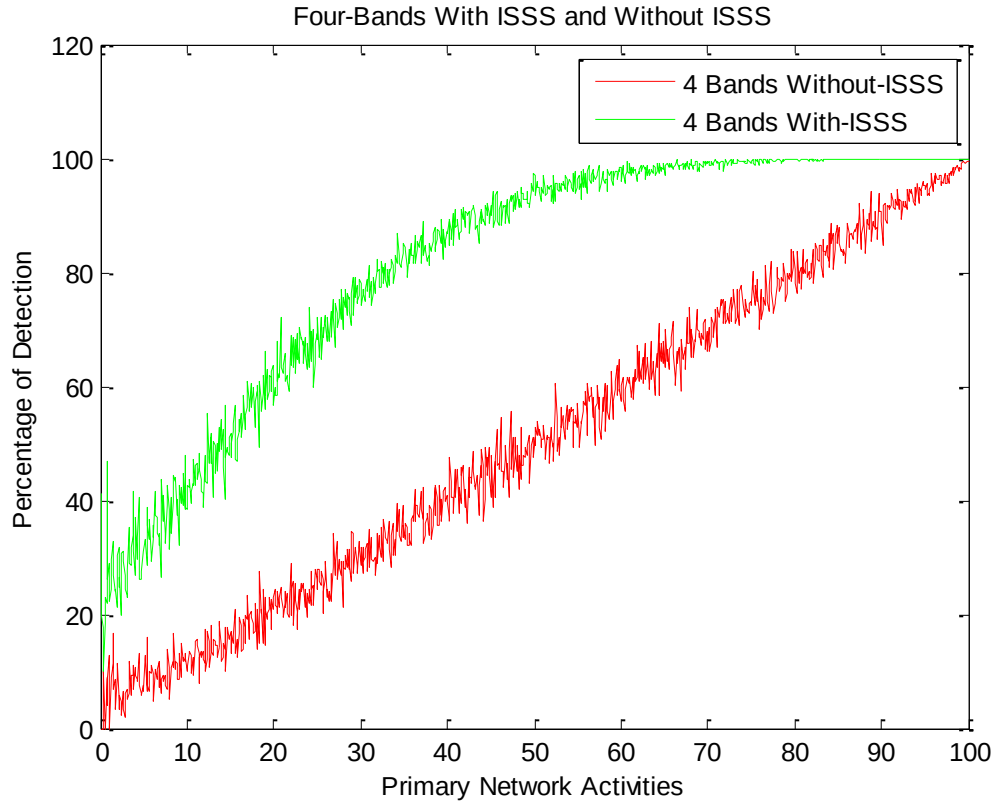


Figure 4.4: ISSS 4-Bands to reduce interference vs. primary network activity

Figure 4.4 shows the percentage of detection when using 4 bands, start with the different value of percentage of detection again its better when using ISSS algorithm at different primary user activity.

As illustrated at the figures in section 4.4.1 , the value of percentage of detection is difference when using different number of bands , at the very low primary user activity the percentage of detection in two bands its better than three and four bands , because the probability of interference is low when using lower number of bands. After increasing the activity, the percentage of detection increases differently without using ISSS, but the value of percentage of detection in the four bands its better than three and two bands when applying ISSS algorithm.

4.4.2 Interference Reduction

Figure 4.5 shows the contribution of the ISSS algorithm in reducing interference with the primary user. The contribution is calculated according to the equation (4.1).

$$ISSS_contribution = I_{ISSS} - I_{single} \quad (4.1)$$

Where I_{single} is the interference detection probability before applying ISSS algorithm, and I_{ISSS} is the interference detection probability after applying the algorithm.

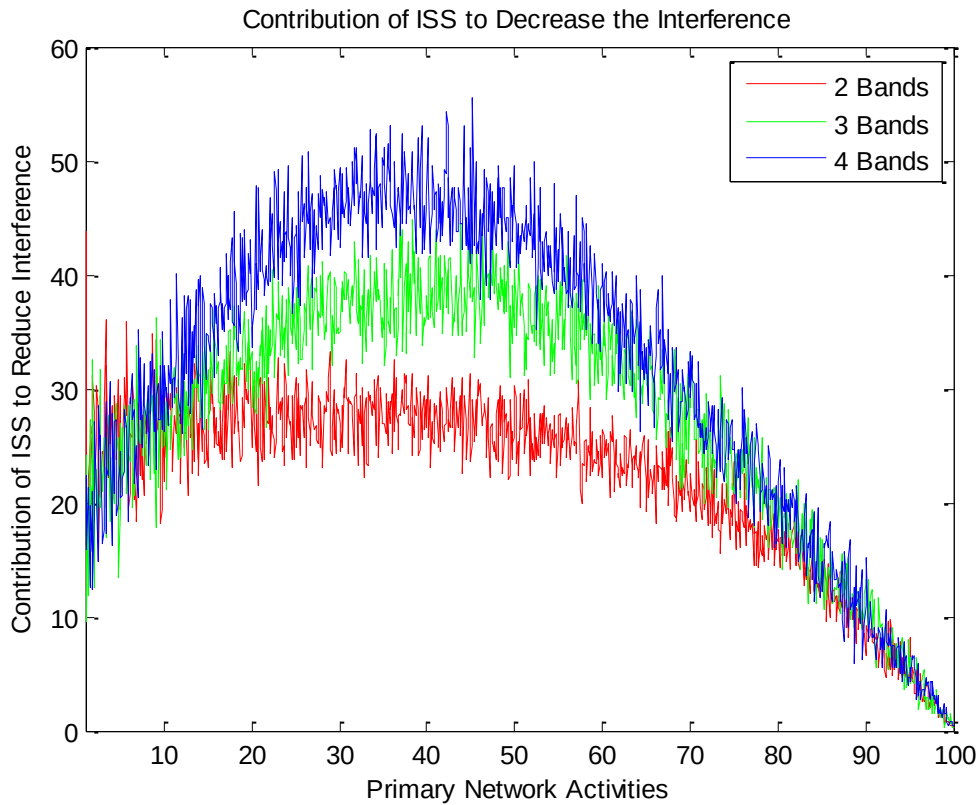


Figure 4.5: ISSS contribution to reduce interference vs. primary network activity

As illustrated at the figure, the different numbers of bands start almost with the same contribution at the very low primary user activity, but after increasing the activity, the probability of detection increases differently. So the system with highest number of band achieve a greater contribution faster than a few bands system, then the contribution decrease because the cooperative system already reached about 100% detection probability but the single band is still increasing. When the primary user activity reaches 100% there is no deference between the ordinary sensing method and the ISSS method that is because the sensing in going to be scheduled at the exact same time as the primary user signal appears, regardless of the sensing schedule.

4.5 Probability of false alarm

Figure 4.6 shows the relation between false alarm probability and primary user activity.

The figure illustrate that increasing the number of bands will increase the false alarm probability, also at low primary user activity the probability of false alarm take the highest value and start decreasing with activity increasing until it reach 0% at the 100% activity because the band is already occupied and there is no opportunity to be missed.

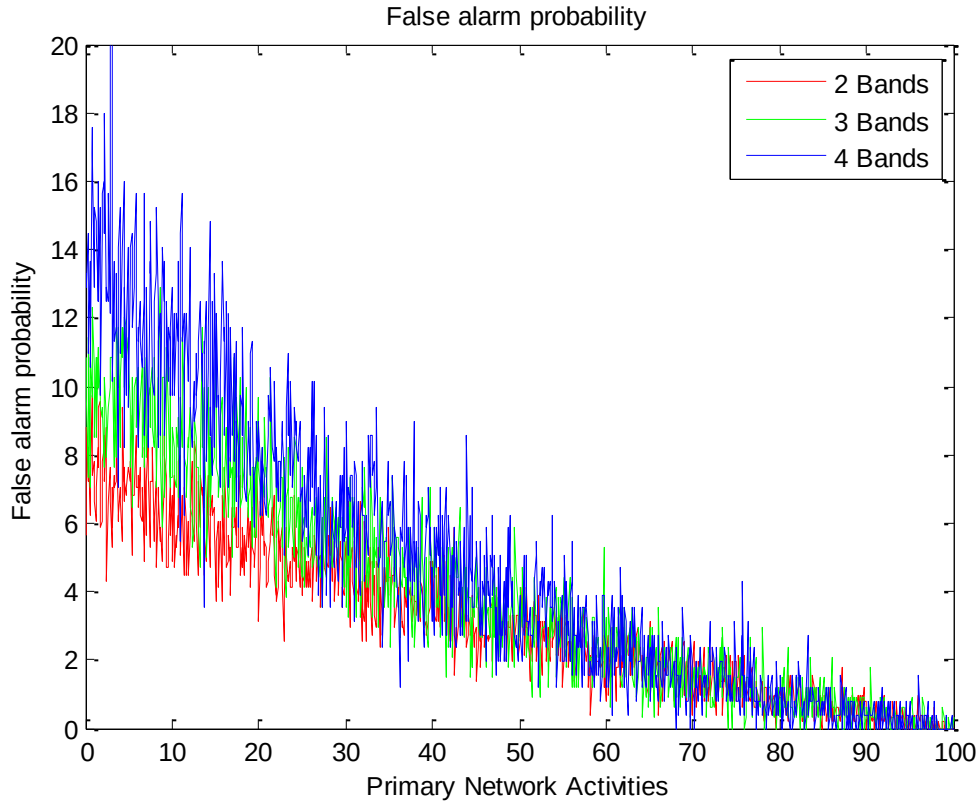


Figure 4.6: Probability of false alarm

4.6 Various primary user activities results

Table 4.1 shows the performance metrics according to different number of bands at 5dB SNR channels with a various primary user activities 20%, 40%, 60% and 80%.

Table 4.1: performance metrics with 5dB SNR

No. of Bands	20%		40%		60%		80%	
	Pd %	Pf %	Pd %	Pf %	Pd %	Pf %	Pd %	Pf %
2	59.75	3.12	74.64	2.78	86.27	1.31	96.37	0.53
4	61.24	5.07	86.91	3.12	98.14	1.95	99.7	0.68
6	72.36	6.73	95.21	3.66	97.87	2.19	99.43	1.1

8	81.83	8.39	98.24	4.49	100	2.22	100	1.38
---	-------	------	-------	------	-----	------	-----	------

By deploying different SNR value, the performance metrics (P_d , P_f) values varies too, when SNR increases the probability of detection increases and the false alarm probability decreases and vice versa. Considering that the variations are applied to noise only, then by increasing the SNR to 10dB, the performance of the system will change as illustrated in table 4.2.

Table 4.2: performance metrics with 10 dB SNR

No. of Bands	20%		40%		60%		80%	
	Pd %	Pf %	Pd %	Pf %	Pd %	Pf %	Pd %	Pf %
2	61.84	1.84	72.56	1.28	86.20	0.42	96.08	0.15
4	63.65	3.05	86.87	1.95	97.42	1.01	100	0.23
6	73.34	3.86	95.03	2.10	98.20	1.17	99.43	0.58
8	84.21	4.68	98.59	2.35	100	1.25	100	0.625

Chapter Five

Conclusion and Future works

5.1 Conclusion

The real challenge is not the frequency spectrum scarcity but the inefficient spectrum utilization. Spectrum sensing is a crucial element in CRNs since it detects the opportunities in the spectrum. The ISSS algorithm is an attempt to improve the spectrum-sensing task through the multiband cooperative sensing.

In this thesis, ISSS algorithm was simulated and evaluated in terms of the contribution to reduce the interference with the primary user as well as the opportunity losses, and it is worth mentioning that the simulation results have gotten in the worst case of the PU activity. In reality the PU activity are less random.

So far, this algorithm assume that there is no means of interaction between the primary user and the secondary users, thus all the scheduling and resource sharing is a secondary network task.

5.2 Recommendation for Future Works

This thesis evaluates the ISSS algorithm based on inductive reasoning approach, however, the following is recommended for future work:

- For the evaluation of false alarm AWGN noise is considered, however, it is recommended to include other types of noise and to measure the detection probability based on that.
- ISSS scheduling algorithm uses energy detection, it is recommended to incorporate other sensing methods such as interference temperature to mitigate the waste of opportunities.

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Appendices

```

clear all
close all
for i=1:1000
    Result_ISS4 = ISSa(1024,4,1,i/1000);
    Result_ISS3 = ISSa(1024,3,1,i/1000);
    Result_ISS2 = ISSa(1024,2,1,i/1000);

    t(i)=i/10;

    Single_Interference_4 (i) = Result_ISS4(1);
    Single_Interference_3 (i) = Result_ISS3(1);
    Single_Interference_2 (i) = Result_ISS2(1);
    ISS_Interference_4 (i) = Result_ISS4(2);
    ISS_Interference_3 (i) = Result_ISS3(2);
    ISS_Interference_2 (i) = Result_ISS2(2);

    Diff_4(i) = Result_ISS4(2) - Result_ISS4(1);
    Diff_3(i) = Result_ISS3(2) - Result_ISS3(1);
    Diff_2(i) = Result_ISS2(2) - Result_ISS2(1);

    FA_4(i) = Result_ISS4(3) ;
    FA_3(i) = Result_ISS3(3);
    FA_2(i) = Result_ISS2(3);

end

% four ands comparison
figure ;
plot(t,Single_Interference_4,'r','DisplayName','Single_Interference_4');hold
on;plot(t,ISS_Interference_4,'g','DisplayName','ISS_Interference_4');hold off;
title('Four-Bands With ISSS and Without ISSS')
axis([0 100 0 120]);
xlabel('Primary Network Activities');
ylabel('Percentage of Detection');
legend('4 Bands Without-ISSS','4 Bands With-ISSS');

% three bands comparison
figure ;
plot(t,Single_Interference_3,'r','DisplayName','Single_Interference_3');hold

```

```

on;plot(t,ISS_Interference_3,'g','DisplayName','ISS_Interfe
rence_3');hold off;
title('Three-Bands With ISSS and Without ISSS')
axis([0 100 0 120]);
xlabel('Primary Network Activities');
ylabel('Percentage of Detection');
legend('3 Bands Without-ISSS','3 Bands With-ISSS');

% two bands comparison
figure ;
plot(t,Single_Interference_2,'r','DisplayName','Single_Inte
rference_2');hold
on;plot(t,ISS_Interference_2,'g','DisplayName','ISS_Interfe
rence_2');hold off;
title('Two-Bands With ISSS and Without ISSS')
axis([0 100 0 120]);
xlabel('Primary Network Activities');
ylabel('Percentage of Detection');
legend('2 Bands Without-ISSS','2 Bands With-ISSS');

%'Contribution of ISS to Decrease the Interference'
figure;
plot(t,Diff_2,'r','DisplayName','Diff_2');hold
on;plot(t,Diff_3,'g','DisplayName','Diff_3');plot(t,Diff_4,
'b','DisplayName','Diff_4');hold off;
title('Contribution of ISS to Decrease the Interference')
axis([1 100 0 60]);
xlabel('Primary Network Activities');
ylabel('Contribution of ISS to Reduce Interference');
legend('2 Bands','3 Bands','4 Bands');

%False alarm probability
figure ;
plot(t,FA_2,'r','DisplayName','FA_2');hold
on;plot(t,FA_3,'g','DisplayName','FA_3');plot(t,FA_4,'b','D
isplayName','FA_4');hold off;
title('False alarm probability')
axis([0 100 0 20]);
xlabel('Primary Network Activities');
ylabel('False alarm probability');
legend('2 Bands','3 Bands','4 Bands');

function ISSS =ISSA(t,n,m,a)
% t = simulation time
% n = Number of available bands

```

```

% m = channel or State number, allways = 2, then m=1;
% a = Primary network activity
clc,close all
SNR=5;

% Initiation           % initial value, start @ level i
i=0;
time(1)=0; % start at time 0
ChStatus(1)=i; % @ time 0 : level i

for x=1:n
    for y=1:t
        signal(y)=sin(y);
    end
    %noise(x,:)=abs(awgn(signal,SNR)-signal(y)); %generate
noise
    noise(x,:)=abs(awgn(signal,SNR)-signal(y));
    th(x)=sqrt(2*(sum(noise(x,:))/t)^2*log(1/0.06));
%calculate energy detection threshold
end
for band =1:n
    for k=2:t
        if rand <= a;
            if i < m
                i=i+1; % Birth Occure
            end
            elseif i > 0
                i=i-1; % Death Occure
            end
        end
        % Primary NW Activities
        ChStatus(band,k)=i;
        time(k)=k;
    end
    %plot the process
    %if n >1
    %    h=ceil(sqrt(n));
    %    g=round(sqrt(n));
    %    subplot(h,g,band)
    %stairs(time, ChStatus(band,:));
    %axis([0 t 0 2])
    %xlabel('Time')
    % ylabel('Channels')
    %end
end
for x=1:n
    for y=1:t
        if noise(x,y)>th(x)

```

```

        NChStatus(x,y)=1;
        if ChStatus(x,y)== 0
            diff(x,y)=1;
        else
            diff(x,y)=0;
        end
    else
        NChStatus(x,y) = ChStatus(x,y);
        diff(x,y)=0;
    end
    FA(x)=0;
end
end
%figure(2)
%subplot(h,g,x)
%stairs(time, NChStatus(x,:));
%axis([0 t 0 2])
%xlabel('Time')
%ylabel('Channels')

% ISS behaviour, n = number of sensor i.e. CR-CPEs

for x=1:n
    for y=1:t/n^2 % sensors time slots
        q=0;
        for j=0:n-1
            if NChStatus(x,n^2*y-n^2+x+j*n) > 0
                if diff(x,n^2*y-n^2+x+j*n)==1
                    if q==0
                        FA(x)=FA(x)+1;
                    end
                    q=1;
                    continue;
                end
                sensematrix(x,(y-1)*n^2+1:y*n^2)=j+1;
                if j+1==x
                    sensesingle(x,(y-1)*n^2+1:y*n^2)=j+1;
                else
                    if NChStatus(x,n^2*y-n^2+x+(x-1)*n) > 0
                        if diff(x,n^2*y-n^2+x+(x-1)*n)~=1
                            sensesingle(x,(y-
1)*n^2+1:y*n^2)=x;
                        end
                    end
                end
                break
            else

```

```

        sensematrix(x, (y-1)*n^2+1:y*n^2)=0;
        sensesingle(x, (y-1)*n^2+1:y*n^2)=0;
    end
end
%IdleCH(band,l)= m-i;
%opportunity = opportunity + length(sensematrix(x
==0,:));
end

for z=1:t
    time(z)=z;
end

%    figure(3)
%    subplot(h,g,x)
%    stairs(time, sensematrix(x,:))
%axis([0 t 0 n+1])
end

% ISS performance

for x=1:n
    N_Idle(x) = 0;
    % Percentage of the Busy & Idle states
    for y=1:t/(n^2)
        if ChStatus(x , (y-1)*n^2+1:y*n^2) == 0
            N_Idle(x)=N_Idle(x)+1;
        end
    end
    N_Busy = (t/n^2) - N_Idle;

    % percentage of detection by single goup
    N_Single(x) = sum(sensesingle(x,)==x);

    %    percentage of detection by ISS
    N_ISS(x) = sum(sensematrix(x,~0);
end
% % percentage of detection by single goup

P_Single = 100*N_Single/(n^2*N_Busy);
P_ISS     = 100*N_ISS / (n^2*N_Busy);

FixPercentage = P_Single / P_ISS ;% 1/ N. of Bands % here
is 25%

Interfernce_Single = 100*(N_Busy - N_Single/n^2)./N_Busy;
Interfernce_ISS    = 100*(N_Busy - N_ISS/n^2)./N_Busy;

```



```

ISS_contribution = Interfernce_ISS - Interfernce_Single ;
ISS_contribution_dB = 20 * log10 ( ISS_contribution);
ChStatus = ChStatus;
sensematrix = sensematrix ;

avg_fa=0;
for x=1:n
    FA(x)=FA(x)/( t/n^2)*100;
    avg_fa=avg_fa+FA(x);
end
avg_fa=avg_fa/n;
ISSS = [P_Single,P_ISS,avg_fa];

```