Optimization of Spectrum Sensing Technique in Cognitive Radio

A Thesis submitted to Gujarat Technological University

For the Award of

Doctor of Philosophy

In

Electronics and Communication Engineering

By

Avani Arvind Vithalani

Enrollment No. 149997111001

Under supervision of

Dr. C. H. Vithalani

GUJARAT TECHNOLOGICAL UNIVERSITY
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DECLARATION

I declare that the thesis entitled **“Optimization of Spectrum Sensing Technique in Cognitive Radio”** submitted by me for the degree of Doctor of Philosophy is the record of research work carried out by me during the period from **May 2015 to June 2021** under the supervision of **Dr. C. H. Vithalani** and this has not formed the basis for the award of any degree, diploma, associate ship, fellowship, titles in this or any other University or other institution of higher learning.

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Name of Research Scholar: **Avani Arvind Vithalani**

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The viva-voce of the PhD Thesis submitted by **Avani Arvind Vithalani** (Enrollment No. **149997111001**) entitled **“Optimization of Spectrum Sensing Technique in Cognitive Radio”** was conducted on 01/06/2021, Tuesday at Gujarat Technological University.

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(Dr. Sunil Agrawal)

1) External Examiner

U. Sripati Acharya

(Dr. U. Sripathi Acharya) 1/06/2021

2) External Examiner

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Abstract

Radio Resource is one of the prime resources of wireless communication and always scarce. Due to rise in number of users day by day and rapid development in wireless technology, available spectrum is not enough to meet current requirements. Cognitive Radio is the concept to overcome spectrum scarcity problem. Cognitive radio users use the underutilized spectrum of licensed user in an opportunistic manner, which is the core idea behind the Cognitive Radio (CR). Spectrum sensing is the major task in CR networks. Spectrum sensing observes the licensed user's existence (signal) and identifies the available vacant spectrum to be used by cognitive radio users.

Cooperative Spectrum Sensing (CSS) technique is widely used because it has capability to enhance detection accuracy in case of multipath fading and hidden terminal problem. This technique is based on sharing information about channel activities among various Secondary Users (SU) in the network. The local spectrum sensing information sent by the CR users is collected at the Fusion Center (FC) by conventional Soft Decision Fusion (SDF) techniques or conventional Hard Decision Fusion (HDF) techniques. In CSS, sharing of local spectrum sensing result between the cognitive users and the FC is challenging process for which the performance of cooperative detection is decided. In this research work, Soft Decision Fusion (SDF) technique Equal Gain Combining (EGC) and Hard Decision Fusion (HDF) technique logical OR is applied to determine the presence of Primary User (PU).

In this research work, Energy detection technique in cooperative manner is used for spectrum sensing and an advanced optimization technique Jaya algorithm is applied to get the minimum Probability of Error. Comparison with other optimization techniques like Teaching Learning Based Optimization (TLBO) further elaborates the fact that Jaya algorithm utilized for optimizing CSS problem converges with less computational complexity in smaller number of iterations with reduction in probability of sensing error. In our research work, TLBO gives 0.29 Probability of Error at threshold value of 10 in 20 iterations. Proposed Jaya algorithm gives the value of Probability of Error 0.23 at threshold value of 8 in just 16 iterations. Thus, Jaya algorithm achieves 20% reduction in Probability of Error compared to TLBO.

Additionally, the best spectrum for secondary users from various available spectrums is selected using Analytic Hierarchy Process (AHP) as well as using combination of AHP and

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods in this research work.

Keywords: Cognitive Radio, Cooperative Spectrum Sensing, Energy Detection, TLBO, Jaya Algorithm, AHP, TOPSIS

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I am very thankful to my supervisor **Dr. C. H. Vithalani**, Professor and Head, Electronics and Communication Engineering Department, Government Engineering College, Rajkot for his continuous encouragement and guidance which inspires me to work continuously and improvise it. He shared his valuable experience and guided me to complete this work effectively.

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I also acknowledge thanks to Honorable Vice Chancellor, Registrar, Controller of Examination, Dean Ph.D. section and all staff members of Ph.D. Section of Gujarat Technological University (GTU) for their assistance and support.

Lastly, I would like to say thanks to Maulesh, my husband, who always stood by my side in all difficult time and provided moral support and encouragement to complete this journey of research work.

As it is a prolonged journey, maybe I have forgotten few names to consider, but they remain a core part of this task, and I seek forgiveness for the same and offer my kind respect to every one of them.

Thanking you,

Avani A. Vithalani

Table of Content

List of Abbreviation

ABC	Artificial Bee Colony
ACO	Ant Colony Optimization
AHP	Analytic Hierarchy Process
AWGN	Additive White Gaussian Noise
BER	Bit Error Probability
BS	Base Station
BSC	Binary Symmetric Channel
CED	Conventional Energy Detector
CFAR	Constant False Alarm Rate
CFD	Cyclostationary Feature Detection
CI	Consistency Index
CR	Cognitive Radio
CRN	Cognitive Radio Network
CSI	Channel State Information
CSS	Cooperative Spectrum Sensing
DE	Differential Evolution
DSA	Dynamic Spectrum Access
ED	Energy Detection
EGC	Equal Gain Combining
FC	Fusion Centre
FCC	Federal Communications Commission
GA	Genetic Algorithm
HDF	Hard Decision Fusion
HS	Harmony Search
IEEE	Institute of Electrical and Electronics Engineers
IED	Improved Energy Detector
MF	Matched filter
MOO	Multiple-Objective Optimization
MRC	Maximum Ratio Combining
NP	Neyman-Pearson
NSF	National Science Foundation

PDF	Probability Density Function
PHY	Physical Layer
PSD	Power Spectral Density
PSO	Particle Swarm Optimization
PU	Primary User
RF	Radio Frequency
ROC	Receiver Operating Characteristic
SDF	Soft Data Fusion
SMC	Spectrum Management Center
SNR	Signal to Noise Ratio
SOF	Single-Objective Function
SU	Secondary User
TLBO	Teaching Learning Based Optimization
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TWS	TV White Spaces
WLAN	Wireless Local Area Network
WRAN	Wireless Regional Area Network

List of Symbols

Symbol	Description
P_e	Probability of error
P_d	Probability of detection
P_f	Probability of false alarm
P_m	Probability of miss detection
h	Channel gain
τ	Sensing time
H_0	Null hypothesis
H_1	Alternative hypothesis
Li	Index of quantization level
Υ	SNR
N	Number of cooperative users
n(t)	The additive white Gaussian noise
n	Number of observations in respective quantization level
Γ (.)	Gamma function
Γ (., .)	Incomplete Gamma function
TW	Time bandwidth product
λ	Detection threshold
Q (.)	Marcum Q-function

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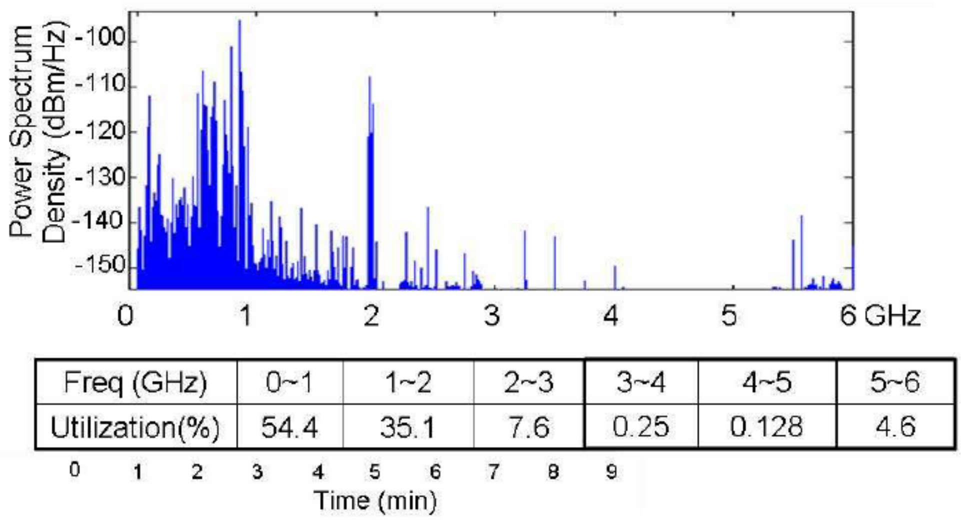
CHAPTER-1

Introduction

1.1 Overview

Due to rise in number of users day by day and rapid development in wireless technology, available spectrum is not enough to meet current requirements. The licensed users do not utilize the spectrum effectively and some of the holes remain vacant because of conventional fixed spectrum assignment policy assigned by Federal Communication Commission (FCC) as shown in Figure 1.1. So, the necessity is that the spectrum utilization should be effective enough to meet the growing demands from users. So, FCC has published a report by designing new spectrum strategies to solve the problem of overcrowded bands and allow secondary users to use licensed bands accordingly.



Freq (GHz)	0~1	1~2	2~3	3~4	4~5	5~6
Utilization(%)	54.4	35.1	7.6	0.25	0.128	4.6

Figure 1.1 Spectrum Utilization

The usage of spectrum is concentrated on certain portions of spectrum bands whereas considerable portion of spectrum remains unutilized. Hence to improve the effective utilization of spectrum in real time and provide efficient communication the concept of Cognitive Radio technology is introduced. Secondary users utilize the spectrum when the primary users are not using it in Cognitive Radio (CR). Cognitive radio has the capability of sensing the spectrum in the real time environment.

By changing its various parameters, CR can acquire information from the environment and gets adapted to the environment accordingly. Thus, a cognitive radio can sense the spectrum in a better way. Main objective of the cognitive radio is to sense the spectrum, learn from the environment and adapt to the environment. Primary users, has the highest priority for the spectrum usage. Secondary users have to vacant the spectrum as soon as primary users appear. Secondary users cannot interferer the operation of the primary users [1].

The following categorization shows the main functions of Cognitive Radio:

1. Radio Scene Analysis: Unused frequency band is detected in this task.
2. Chanel State Estimation: This is used to find the channel.
3. Spectrum Management: The main aim of this function is to effectively share the spectrum of the free channels, which are detected while spectrum sensing.

The principal function of the cognitive radio is the process of searching the primary users' spectrum which is in use. Unused portions of licensed spectrum are known as spectrum holes or White Spaces. After the identification of the white spaces, the best channel which is available and which meets the Quality of Service (QoS) requirements and its communication, must be selected by the cognitive user. Now, when the CR user occupies the channel and at the same time the licensed user i.e. primary user wants to use this channel, then the CR user must end their transmission and change to another channel which is unused as the primary user (spectrum mobility) is on higher priority. The scheduling mechanism in the CR network ensures that all the CR users get equal opportunities for using the spectrum (spectrum sharing).

1.2 Heterogeneous Wireless Access Networks and Cognitive Radio

Advanced wireless networks will have following attributes [2]:

• **High Transmission Rate:**

Higher data rate is the prime requirement of future wireless services. High data rate is required to support a greater number of users with less transmission time. Increase in data rate should not increase spectrum bandwidth or transmit power requirement. There are many methods in the physical layer to increase data rate.

• **QoS Support:**

QoS support is required to prioritize and differentiate between various types of traffic like voice, data and video. Because all these types of traffic are supported by the advanced wireless systems and priority is decided base on the performance requirement. Designing of appropriate radio resource management is necessary to access the available spectrum efficiently.

• **Cross-Layer Design:**

To create a link among various protocols in various layers [3] [4], and to decrease the overhead in the protocol stack, the cross layer design is proposed. Improvement in the data rate, radio resource utilization and error reduction are improved. Thus, overall system performance is achieved by designing a cross layer. Also, wireless system can be optimized throughout the protocol stack.

• **Integration of different Wireless Access Technologies:**

Future generation wireless networks will be heterogeneous. It will use IP technology to support various wireless access technologies for a converged wireless system. With this system, it is required for a mobile device to connect with different wireless networks simultaneously using different access technologies. For example, a mobile is connected to a cellular network, but when it moves out of the range of the cellular network, it can connect to a WLAN through the IEEE 802.11 based network or a WiMAX network if available to continue the communication. There are two advantages of such system: 1.

Seamless mobility is possible anywhere and anytime. 2. Data rate is increased as multiple data streams are transmitted concurrently.

Apart from above advantages, there are few issues related to research in such environment where different networks coexist. Some of the research issues are network selection [5], bandwidth allocation [6] , admission control [7] , QoS support [8] [9], vertical handoff [10] [11] [12] , and routing [13]. In such heterogeneous network, the mobile unit should be connected to particular set of networks to increase its utility. Another issue is on the part of service providers. Seamless connectivity with admission control and mobility management is necessary. Also, service providers try to increase their revenue and for that all users in different service areas should be allocated the available bandwidth efficiently for optimum use of radio resources.

• **Software-Defined Radio and Cognitive Radio:**

The concept of cognitive radio is that, some frequency bands are highly occupied and some bands are lightly occupied as per application. The frequency spectrum is the valuable resource and its efficient use is the prime requirement in all next generation wireless systems. With the traditional allocation of frequency bands to various applications, all frequency bands cannot be utilized efficiently. Due to unequal traffic on different bands, spectrum opportunities are generated. Cognitive radio implemented on software defined radio can exploit these opportunities in an intelligent and adaptive manner. Cognitive radio uses dynamic spectrum access so that wireless transmitter receiver can change its operating parameters like transmit power or operating frequency to be compatible with different operating environments. By implementing intelligent algorithms to observe, learn, optimize and then decide [1], cognitive radio makes the transmission possible. All mobile units or wireless node have to use cognitive capabilities throughout the protocol stack. Cognitive radio is indeed a significant component for future wireless networks.

Knowledge of various engineering disciplines is necessary to implement cognitive radio technology based on dynamic spectrum access. By having multidisciplinary knowledge, the desired design objective of cognitive radio can be achieved. Multiple scientific and engineering disciplines include knowledge of optimization, machine learning, game theory and economics in addition to the traditional wireless communication knowledge.

• **Integration of Cognitive Radio concepts in traditional Wireless Systems:**

Traditional static spectrum allocation wireless communication if integrated with advanced cognitive radio with dynamic spectrum access, system performance can be improved due to optimum utilization of radio resources. For example, with integration of cognitive radio using dynamic spectrum access, load balancing or dynamic channel selection is possible in traditional WLANs as well as traditional cellular system. Also, for UWB systems, transmit power control and for OFDM distributed subcarrier allocation is possible with cognitive radio.

• Emergence of Cognitive Radio-based Wireless Applications and Services:

The following are services and applications of cognitive radio.

1. Advanced Wireless Internet Services:

Cognitive Radio based on dynamic spectrum access is best suited for next generation wireless internet service because it requires seamless connectivity with QoS to multiple mobile users for a large number of multimedia applications.

2. Wireless Intelligent Transportation Systems (ITS):

Wireless transportation system is used to avoid road traffic congestion by providing traffic information to vehicles. The intelligent Transportation System is an integrated wireless communication and software system for information exchange. It improves safety and efficiency of transportation by vehicles. One example of wireless communication in ITS is shown in figure 1.2 below. In these systems, vehicles can form Vehicular Ad-hoc Network (VANET) to communicate with other vehicles to get the information of traffic locally. Also, vehicles can contact roadside base station to get or provide the information about traffic which would be useful for selecting a proper route. IEEE 802.11 is used for vehicle to vehicle communications [14] and WiMAX is used for Vehicle to roadside communications [15]. As high mobility is the main feature of transportation system, designing of wireless communication for this system and its mobility management is very challenging task. Intelligent and fast dynamic spectrum access can improve the system performance of transportation systems.

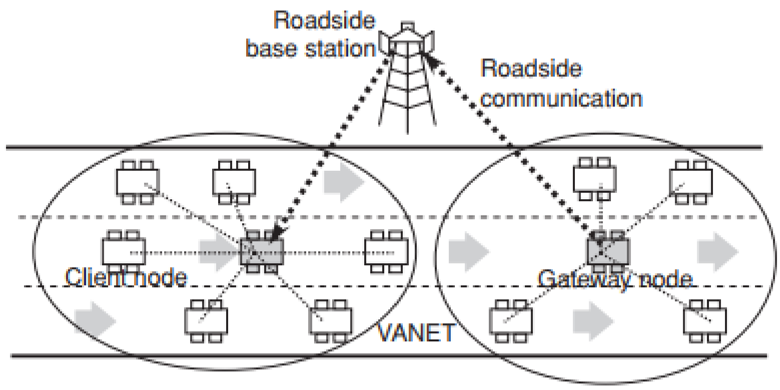


Figure 1.2 Wireless communications in Intelligent Transportation Systems.

3. Wireless e-Health Services:

Healthcare services can be greatly improved by using the wireless technologies. Through these wireless services data can be shared between physician, medical staff and patient, even though they are in different hospitals. As an example, bio signal sensors are attached to patients which transmits data e.g. heart rate and blood pressure to a doctor at a health care center. This data is used for various diagnosis. It can also monitor the patient from a remote place. The technology which can be used for such remote (patient is at home or hospital) diagnosis and monitoring is WLAN and WPAN [16]. For patients in ambulance the technology used is cellular network and WiMAX [17] [18] [19] [20]. There is always electromagnetic interference (EMI) in such conditions, which could be very harmful. Hence Cognitive radio technology based on dynamic spectrum access is very useful for providing wireless communication services in health care services.

4. Public Safety Services:

Public safety services must be given priority over other commercial services. For communication for public safety services, cognitive radio technology based on dynamic spectrum access is suitable [21].

1.3 Introduction to Cognitive Radio

Cognitive Radio is the system which utilizes the spectrum of radio frequency to the fullest [22]. At present there is increasing demand of frequency spectrum, whereas there is dearth of available frequency spectrum. The use of wireless applications is increased by the mobile users in recent scenario. Only a small part of available radio spectrum, can be licensed to new wireless applications as most part is already allocated. The Spectrum Policy Task Force (SPTF) of the Federal Communications Commission (FCC) studied about the frequency band. They found that in certain locations and at certain times, many frequency bands are scarcely occupied [23]. However, there are some frequency bands which are heavily used by licensed systems. As an example, in USA [24] [25] [26], the spectrum bands of cellular networks are heavily used in working hours. But the same remain unoccupied from 12 am till 6 am.

In spectrum licensing scheme, the spectrum allocation is built on command and control model. This leads to less utilization of the radio spectrum. Now in this scheme, if the radio spectrum which is allocated to licensed user is not utilized, then it cannot be used by the unlicensed user and their application. [27]. Hence only a dedicated spectrum can be used by wireless system. It cannot adjust the transmission band based on different environment. As an example, the wireless system cannot use another lightly used band, when one spectrum band is extensively used.

When a license is given to one licensee, they must abide to the license specification which are power, space, frequency, type of use and duration of license. In the present spectrum licensing scheme, the license is restricted to alter the type of use or give rights to another licensee. Hence this leads to limited use of frequency spectrum resulting in low usage of frequency spectrum. This creates spectrum holes or spectrum opportunities (Figure 1.3). The definition of spectrum holes stands as frequency bands which are allocated to, but in certain times and certain locations the licensed users do not utilize them. These frequency bands however can be utilized by unlicensed users [28].

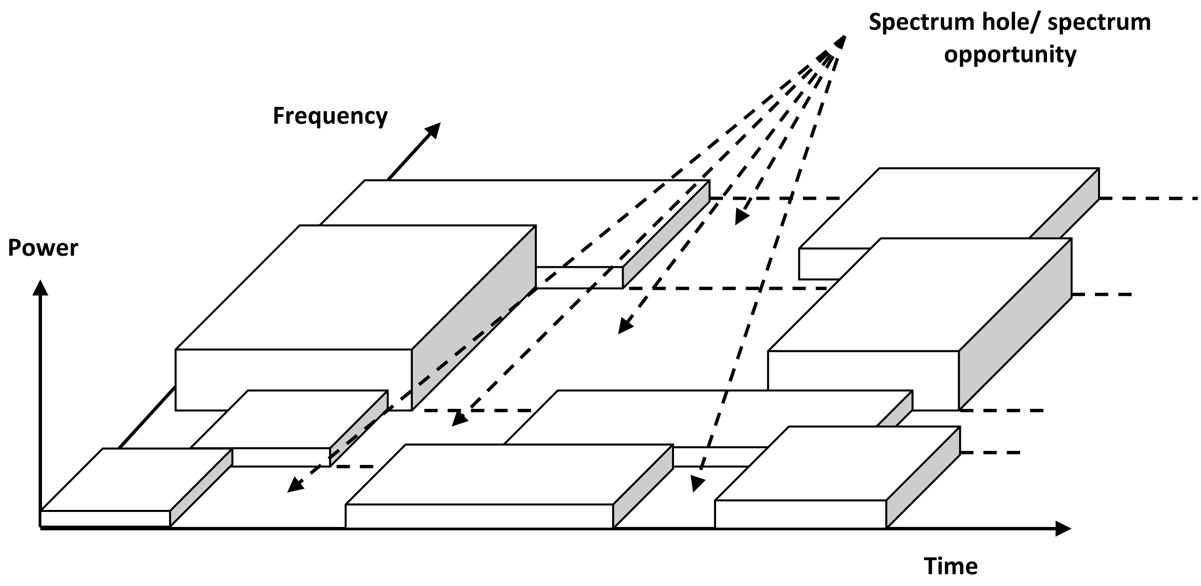


Figure 1.3 Spectrum Hole (or Spectrum Opportunity)

The following summary gives the limitations in spectrum access due to the static spectrum licensing:

- **Fixed type of Spectrum Usage:**

  In the traditional static channel allocation scheme, spectrum usage type cannot be changed. For example, digital TV broadcast or broadband wireless access technologies cannot use a spectrum which is already allocated to analog TV National Television System Committee (NTSC) application even though bands allocated to analog TV is highly underutilized at many locations by licensed users [29].

- **Licensed for Large Region:**

  A spectrum license is assigned in a vast region to service provider. The service providers need return on their investments. Hence, they use the spectrum only on those regions where the subscriber base is higher. Due to this, in other regions the frequency spectrum remains unutilized. Other service providers are not allowed to use this spectrum also.

- **Large chunk of Licensed Spectrum:**

  When a license is allotted to a service provider, it is given in wide range of radio spectrum (e.g. 50 MHz). If a service provider wants to use small spectrum band for a small region for a small amount of time, it’s not possible to obtain such license. As an example, cdma2000 needs bandwidth of 1.25 MHz or 3.75 MHz for temporary wireless access service in a hotspot area. In 3G System, cdma2000 uses 1.25 MHz for 1*RTT. If there is need to increase the data rate then 3.75 MHz is used in 3*RTT.

- **Prohibit Spectrum access by Unlicensed Users:**

  In the present spectrum licensing scheme, the unlicensed users are not allowed to use the unoccupied spectrum of the licensed users. Licensed users are only allowed to use the radio spectrum. As an example, there can be no users in an area in a cell. This area cannot be used by unlicensed users even though they are short range wireless communication and they would not interfere with other users.

The spectrum licensing scheme should be modified, in order to overcome the limitations and to enhance the efficiency and usage of available spectrum. Thus, concept is that, the spectrum access will be flexible enough to allow unlicensed users for accessing the radio spectrum, however under certain restrictions. The design of the present wireless system is based to operate on a particular frequency which is dedicated to it. The improved flexibility by the spectrum licensing scheme will not be used by them. Thus, the idea of cognitive radio came into existence. The cognitive radio through dynamic spectrum access, gives flexibility to the wireless transmission. This results in improved performance of wireless transmission. Also, there is optimal usage of frequency spectrum. The cognitive radio user, uses the information of the target radio spectrum (e.g. present activity of licensed user and the type) through spectrum sensing. This information is utilized by the spectrum management function. Then the information is examined for spectrum opportunities and thereby decisions on spectrum access are made. The spectrum mobility function changes the frequency bands for users of cognitive radio, when there is change in target spectrum.

1.3.1 Software-Defined Radio

Software Defined Radio is the main component for designing Cognitive Radios. SDR is a system in which modulation type, operating frequency and protocol all these transmission parameters can be changed dynamically as per requirement. Such dynamism is achieved through signal processing algorithms which are software controlled. Major functions performed by SDR are given below [28]:

Multiband Operation: Software Defined Radio supports various wireless systems like TV band, cellular band, ISM band [30] etc. working on different frequency spectrum for communication.

Multi Standard Support: Similar to multi band operation, SDR also supports multi standard operation like GSM, WiFi, WiMAX etc. In addition to multi standard, SDR also supports multiple air interfaces in the same standard like IEEE 802.11a, IEEE 802.11g, IEEE 802.11b etc.

Multi Service Support: Software Defined Radio supports various types of services like broadband wireless services and mobile telephone services.

Multichannel Support: Software Defined Radio can operate on various different frequency bands at the same time.

Refer figure 1.4 for general structure of an SDR transceiver. Many components in SDR viz. analog to digital convertor, data and baseband processing are same as that of normal transceivers. In SDR, the difference is that, the components can be controlled from protocols in the top layers. It can also be reconfigured by cognitive radio module. In the transceiver in SDR, the analog signals are received from front end from the antenna. The bandpass filter does filter the analog signal to get the signal in required frequency. Now, amplifying this signal and processing it, an in phase (I) path and quadrature (Q) path are generated, by shifting the phase by $-\pi/2$. The I and Q path signals are then transformed into digital data. The conditions of Nyquist's theorem of sampling has to be satisfied for which the sampling rate of A/D has to be chosen. But to reduce the signal processing overhead, there should be minimized sampling rate. The signal processing algorithms, sampling rate and the parameters of the analog and digital filters can be re-configured according the wireless air interface technology and according to the operating frequency.

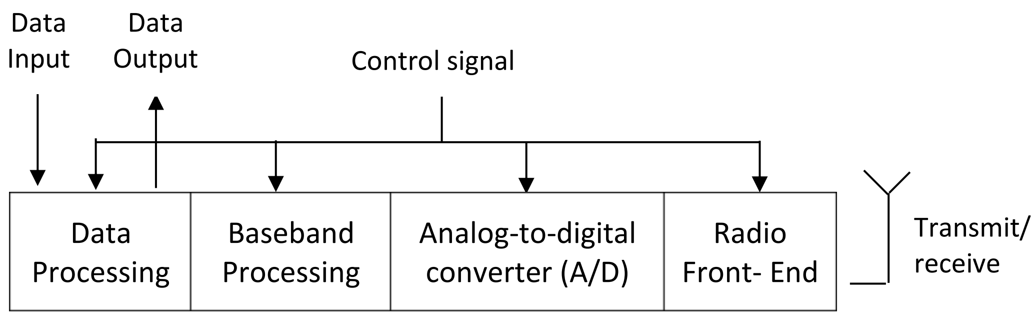


Figure 1.4 SDR transceiver

Reconfiguration of the transmission items in a wireless transceiver can be done in line with the communication needs and specifications.

- The operational standards, frequency band and other radio transceiver parameters can be set prior to the system given to the customer. After the configuration of system, the parameters cannot be changed. One SDR transceiver model can be given to many customers who has different needs, though in this case, there is no support of the dynamic reconfiguration of the system.
- Reconfiguration of radio transceiver parameters can be done few times during the system's lifetime. When a new base station is added or when the network structure is changed are examples wherein reconfiguration can be done.
- Based on connection the radio transceiver parameters can be altered. As an example, the transceiver can select from the various wireless access networks available (GSM, WiFi or WiMAX) based on price, performance and network availability, whenever a user wants to start a wireless Internet connection.
- Based on time slot, the radio transceiver parameters can be dynamically altered. As an example, when the level of interference changes, the transmission power can be altered. The operating frequency band can be altered by the unlicensed user(s) when there is activity of the licensed user(s).

A mobile user will have the option to switch among networks, as in the future the mobile phones will be designed to support many wireless access technologies. In [31] discussion on a design method for an SDR transceiver for multi standard mobile phones is done. The major design constraints were usage of power and space as well as scalability of the equipment. Kansas University Agile Radio (KUAR) is an SDR platform created in [32]. It comprises of converters from analog to digital and digital to analog, RF transceiver, antennas, power supply, control processor and a digital board of programmable signal processor. An operating frequency of 5-6 GHz is supported by radio front end. Running on Linux, the digital board is an embedded PC. To provide ease of applying the signal processing algorithm, a Field Programmable Gate Array (FGPA) is used. In the software portion, KUAR Boot, Policy, Ops and QoS – the radio control and management programs. To load linked radio modules used by other components, the boot program is used. To calculate network parameters viz the traffic load in the protocol lots and the RF environment of the network, the Ops and QoS programs are used. The modulation mode and frequency band can be altered by the Ops program. (e.g. QPSK, QAM-16 and QAM-64). To control the transmission factors within the guidelines, the Policy program is used. To implement a WiMAX 802.16a experimental transmitter and receiver, the KUAR platform was used.

A wider operational spectrum is taken care by the SDR platforms. For example, in [33] in order to efficiently sample a specific spectrum range, the receiver was calibrated to act as a signal conditioner for A/D converters. The frequency spectrum of 800 MHz to 5 GHz is backed by the SDR platform. Development of applications and trial platforms of software defined radio were done in [34] [35] [36] [37] [38] [39] [40].

1.3.2 Cognitive Radio Features and Capabilities:

The application of Cognitive Radio is based on software defined radio. As per definition in [1], Cognitive Radio is defined as: An intelligent wireless communication system which knows its environment. It will learn from environment. It will adapt its internal states to different changes in the existing RF stimuli by adjusting the transmission factors (e.g. frequency band, modulation mode, and transmit power) in real-time and on-line manner. To start communications among cognitive radio nodes or users, the CR network is used. With reference to the change in the topology, operating conditions, user requirements or environment, the communication parameters can be adjusted. There are two main purposes of Cognitive Radio: (1) To accomplish very reliable and very effective wireless communications. (2) To enable enhanced usage of the frequency spectrum.

1.3.2.1 Cognitive Radio Architecture

Figure 1.5 shows the protocol stack of cognitive radio. The application of RF front end is based on software designed radio (SDR transceiver), in the physical layer. The changes in the cognitive radio environment should be known to the adaptive protocols in the MAC, network, transport, and application layers. The differences in channel quality, transmission needs of secondary users and the traffic activity of primary users should be considered by the adaptive protocols. To begin interfaces within the SDR transceiver, adaptive protocols and wireless usage services, a cognitive radio control is used. This is also used to link all modules. Cognitive Radio module uses smart algorithms to convert the calculated signal from the physical layer, and receive data on transmission needs, from the applications to regulate the protocol parameters in the various layers [41].

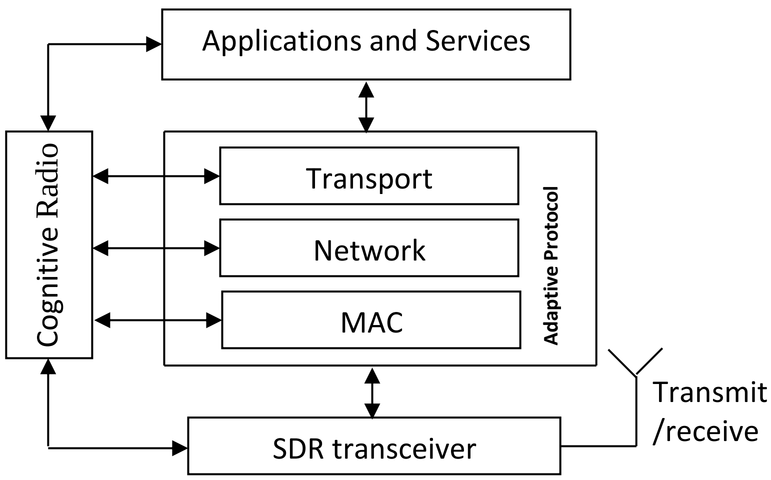


Figure 1.5 Cognitive Radio Protocol Stack

1.3.2.2 Functions of Cognitive Radio

To support intelligent and effective dynamic spectrum access, the main functions of cognitive radio is as below:

• Spectrum Sensing:

The purpose of Spectrum Sensing is to know the status of the spectrum of interest. It also determines the activity of the licensed users by regularly sensing the desired frequency band. The spectrum which is not used or spectrum hole (i.e. band, location and time) is identified by a cognitive radio [42] [43]. The cognitive radio also establishes the method of getting information in it (i.e. transmit power and access duration). This is done without interference to the transmission of a licensed user.

Spectrum sensing can be distributed or centralized. The target frequency band is measured by the sensing controller (e.g. access point or base station) in the case of centralized spectrum sensing. The data thus taken is communicated with other nodes in the system. As all the sensing functions are done at sensing controller, the complication of user terminals is minimized in the centralized spectrum sensing. But location diversity is a problem for centralized spectrum system. As an example, an unlicensed user at the edge of the cell may not be accessed by the sensing controller. However, in case of distributed spectrum sensing [44], the spectrum sensing is done autonomously by the unlicensed users. The data can be used by individual cognitive radios which is non cooperative sensing or it can be shared with other users which is cooperative sensing. A communication and processing overhead are incurred in cooperative sensing, but the perfection of cooperative spectrum sensing is better than that of non-cooperative sensing [45] [46].

• Spectrum Analysis:

To organize the spectrum access by the unlicensed users, the spectrum sensing information is used. To improve the transmission parameters, the communication needs of unlicensed users are used. Spectrum analysis and spectrum access optimization are major factors of spectrum management. In spectrum analysis, the information about the spectrum holes (e.g. time of availability, interference estimation and probability of collision with a licensed user due to sensing error) is gained by analyzing data from spectrum sensing. To get into the spectrum (e.g.

bandwidth, modulation mode, location, time duration and frequency) a decision is made by enhancing the performance of the system, given the required results (e.g. get maximum output of the unlicensed users) and constraints (e.g. balance the interference caused to licensed users below the target level)

- **Spectrum Access:**

  The unlicensed users access the spectrum holes, after a conclusion is made on spectrum access based on spectrum analysis. Based on cognitive medium access control (MAC) protocol, the spectrum access is done. This is to avoid collision with other unlicensed users and also with licensed users. Coordination is done by cognitive radio transmitter with cognitive radio receiver to get the transmission synchronize. This is done in order that the transmitted data can be received effectively. A random-access MAC (e.g. ALOHA, CSMA/CA) [27] or a fixed allocation MAC (e.g. FDMA, TDMA, CDMA) could be the basis for a cognitive MAC protocol.

- **Spectrum Mobility:**

  The function associated with variation of operating frequency band of cognitive radio users is Spectrum Mobility. The unlicensed user can alter a spectrum band which is not in use at present, this is done when a licensed user starts using a radio channel which is at present used by an unlicensed user. This is called spectrum handoff. In spectrum handoff, to match the new operating frequency band, the protocol parameters at the various layers in the protocol stacks have to be changed. The data transmission by the unlicensed user can continue in the new spectrum band, this must be ensured by the spectrum handoff.

1.3.3 Dynamic Spectrum Access

Dynamic access by the unlicensed users is the principle behind implementation of cognitive radio. Dynamic spectrum access is the [47] mechanism of adjustment of usage of spectrum resource in real time according to changes in environment like type of applications and available channel, changes of transmission mode, location and battery status, also according to changes in external parameters like operational policy and propagation [48] [49] [50].

Commons-use, shared-use and exclusive use are three major models of dynamic spectrum access [51] [52] [53] [54]. The commons-use model is used in the ISM band [55]. In this model the spectrum is open for access to all users. On the other hand, in shared use model, frequency bands are allocated to licensed users only. Unlicensed users can access these bands of frequency only when licensed users are not using them. Exclusive use model is better than conventional commons and shared use models. In this model, a primary user can grant access of a particular band to secondary user for a certain period of time [56]. Thus, here the type of use and licensee of the frequency bands changes dynamically.

The secondary user can use unused band without causing interference to the active primary user in opportunistic spectrum access. Opportunistic spectrum access can be performed in two different ways: 1. Spectrum Underlay and 2. Spectrum Overlay.

Transmission power of secondary user is limited in spectrum underlay approach so that they do not cross the interference temperature limit of primary users. One possible way is to use UWB type wide frequency band transmission by secondary users so that with very low transmission power high data rate is achieved.

In overlay spectrum access approach, secondary users have to identify and exploit the spectrum in space, frequency and time to find spectrum holes. In this approach, there is no any restriction on secondary users about transmission power. This approach of spectrum access is suitable with the existing spectrum allocation.

It is possible that the use of commons-use model for dynamic sharing can be between heterogeneous networks or between homogeneous networks. [57] [58]. Symmetric sharing is defined as sharing between all networks in a heterogeneous environment with cognitive or adaptive capabilities. Asymmetric spectrum sharing is defined as [59] [60] [61] sharing between networks in which one or more network is without cognitive or adaptive capability.

Spectrum Exploration (spectrum sensing and analysis) and Spectrum exploitation (decide and handoff) are two main phases of dynamic spectrum access.

1.3.4 Components of Cognitive Radio

As per changing environment, there are mainly four functions performed by cognitive radio to adapt the transmission parameters. These four functions can be represented through cognitive cycle as shown in figure 1.6 [62]. Different components of cognitive radio are shown in figure 1.7.

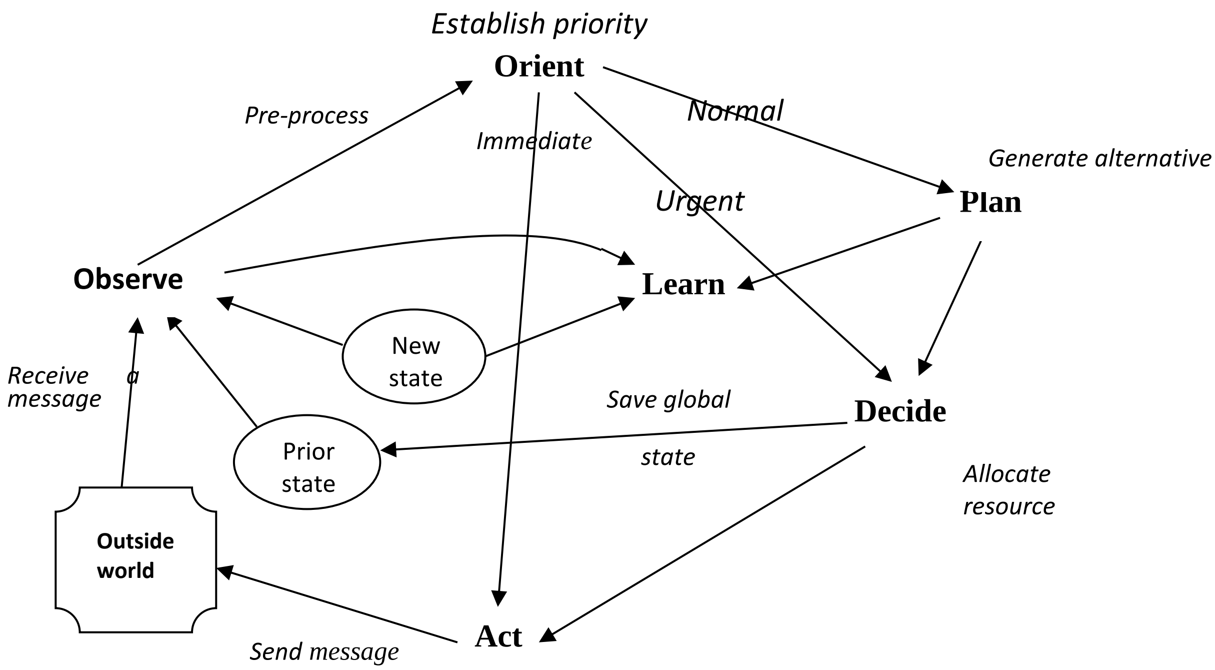


Figure 1.6 Cognitive Cycle

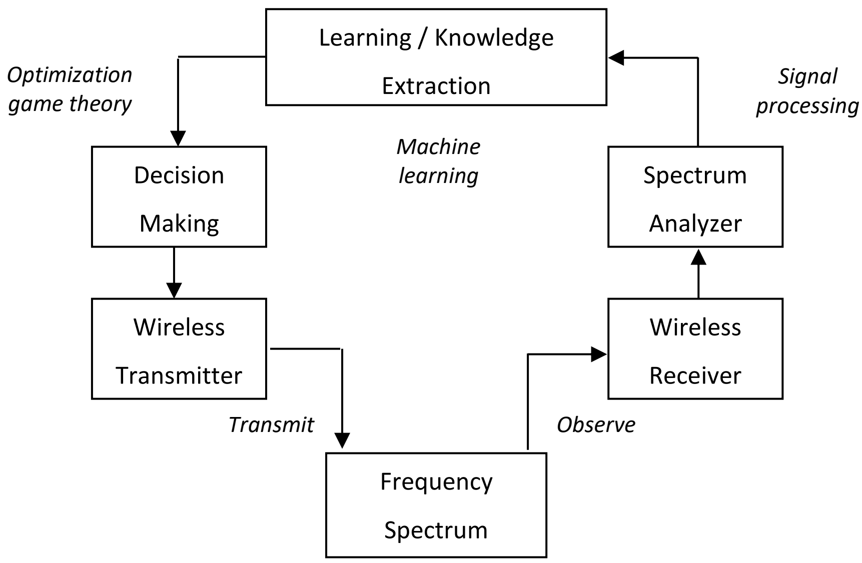


Figure 1.7 Components in a Cognitive Radio node.

- **Transmitter/Receiver:** This component is responsible for the main task of signal transmission and reception. In addition to this, it is also used for spectrum sensing. It checks the activity on the frequency spectrum. Higher layer protocols direct this component to change its parameters dynamically.
- **Spectrum Analyzer:** spectrum analyzer finds the spectrum holes for unlicensed users by detecting the signature of a signal from a licensed user. It is the duty of spectrum analyzer to ensure that the licensed user transmission is not affected if an unlicensed user wants to access the same spectrum. Here, spectrum usage information is obtained using various signal processing techniques.
- **Knowledge Extraction/Learning:** To understand the behavior of licensed users, information on spectrum usage is used by learning and knowledge extraction. To optimize and adapt the transmission parameters, a knowledge base of the spectrum access environment is built and maintained so that the desired objective under various constraints is achieved. Machine learning algorithms can be used for this purpose.
- **Decision Making:** The final stage is decision making. In this stage, the decision about accessing the spectrum is made based on the knowledge of the spectrum usage. This decision depends on unlicensed user's cooperative or competitive behavior. There are different techniques available to find the optimal solution. One of the techniques is to apply optimization theory. This technique is possible when there is single entity with a single objective. In other situation, when there are multiple entities with its own objective, game theory is suitable. In case of random systems, stochastic optimization is applied for decision making.

1.4 Outline of the Thesis

The remaining thesis is organized in the following chapters:

Chapter 2 Provides whole background information related to the research topic. It covers state of art for the topic and extensive literature survey of the method used to date. It also covers shortcomings of those methods and interpretation of those methods. From this literature survey, we have inferred conclusion and later identified problem statement and objective of the work is defined.

Chapter 3 Covers various spectrum sensing techniques used to identify free spectrum. A comparison of all spectrum sensing techniques is also given in this chapter. This chapter also covers various optimization techniques by giving numerical examples. JAYA algorithm with example is also discussed in this chapter.

Chapter 4 Provides extensive discussion as for why we have utilized particular methodology in our work, its merits and demerits are also discussed.

Chapter 5 gives final results of algorithm. Comparison of JAYA algorithm with Teaching Learning Based Optimization (TLBO) is discussed here. It also covers how the best spectrum is selected by using Analytic Hierarchy Process (AHP) and also combination of AHP and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods.

Chapter 6 covers Conclusion, Future Scope of the work and Major Contribution of the thesis.

Chapter 7 shows References and Publications.

CHAPTER-2

Background and Literature Review

2.1 Background Spectrum Sensing

The spectrum hole or white space is usually the temporary idle spectrum which the CR user is able to find during spectrum sensing. However, when licensed user is active for communication, to avoid interference the CR has to use another spectrum hole or the transmission parameters to be changed. The theory of spectrum holes [63] [23] [64] [1] is shown in figure 1.3.

Figure 2.1 shows the basic comparison of sensing methods. The methods based on cyclo-stationary detector are usually not robust than waveform-based sensing. This is because, by using deterministic signal component results in coherent processing. However prior information about the primary users' characteristics should be there and primary users should transmit known patterns or pilots.

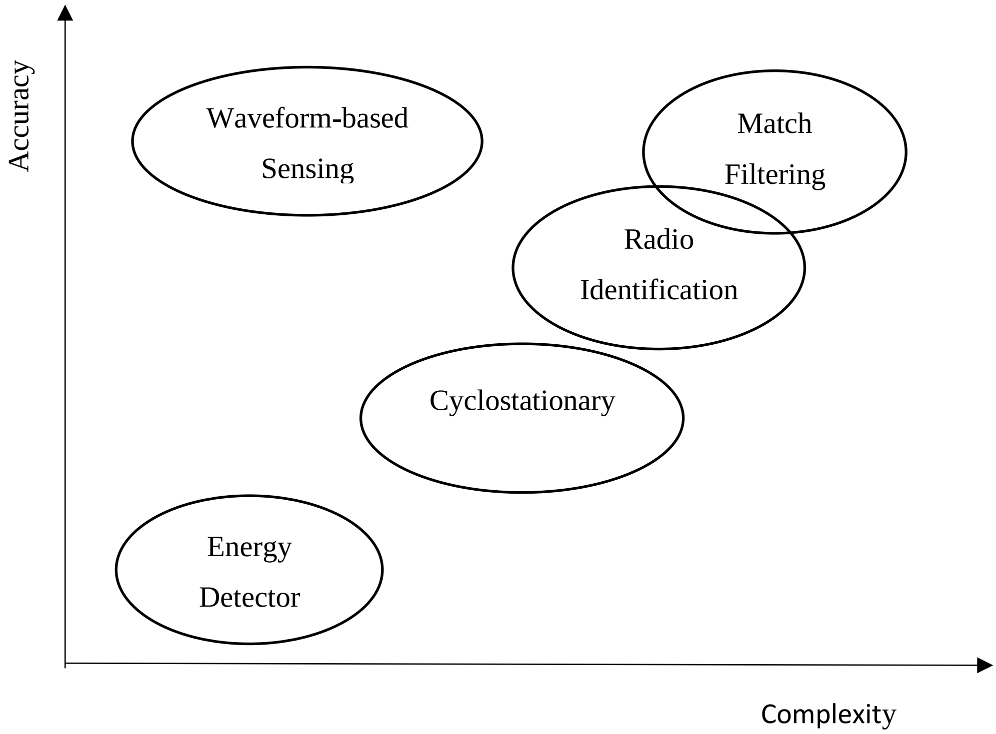


Figure 2.1 Comparison of main Sensing Methods

The receivers do not require any knowledge of the primary users' signal in Energy Detector based sensing. This is the reason behind using energy detector-based sensing in our research work. When two common assumptions do not hold, then the performance of energy-based detector becomes limited. In this case, the variance of noise is not known. Moreover, the noise is also not stationary. The energy-based detector method has other problems also viz filter effects ad spurious tones. As mentioned in literature, while keeping noise stationary, the energy-based detector sensing method performs better than cyclo-stationary spectrum sensing methods. However, when the noise becomes non-stationary which generally happens in presence of co-channel or adjacent channel interferers, the energy-based detector method fails while the cyclo-stationary based algorithm is not affected. In another case, as a result of channel fading, the cyclo-stationary features are completely lost.

So, some tradeoffs should be considered while selecting a sensing method. The main factor in selecting a method is the characteristics of primary users. The required accuracy, network requirements, computational complexity, sensing duration requirements are other factors. The existence of regularly transmitted pilots, timing/frequency characteristics and cyclo-stationary features are all important.

For improving performance of spectrum sensing many optimization techniques are used. The parameters are optimized as per required maximum and minimum criteria. They are optimized through optimization technique.

2.1.1 Research challenges in Spectrum Sensing

There are various physical and MAC layer research issues [2] in spectrum sensing. Physical layer problems are because of Signal processing and MAC layer problems are due to optimization of spectrum sensing.

In the MAC layer, because of broadcast nature of transmission, transmission collisions and performance degradation occur. Various research challenges in spectrum sensing are explained further as below:

Sensing Interference Limit: For interference-based sensing, to decide whether the spectrum is idle or occupied is one of the objectives of spectrum sensing. This spectrum can be accessed by an unlicensed user under the interference constraints if the spectrum is idle. Transmissions from unlicensed users cause interference to licensed receiver. The challenge lies in this measurement of interference. First challenge is the transmitter may not know the existence of the licensed receiver if the receiver is a passive device. Second, the exact location of the licensed receiver may be unknown to the unlicensed user. And location of licensed receiver is necessary to calculate the interference.

Spectrum Sensing in Multiuser Networks: In a multiuser network, multiple networks of licensed and unlicensed users coexist. Due to this coexistence, transmissions in one network may interfere with another network's transmission. In this scenario, cooperative spectrum sensing helps because it can detect the status of the spectrum accessed by differently located licensed users. A spectrum utilization map is obtained based on the spectrum sensing information in cooperative spectrum sensing. This map is utilized by the unlicensed users for their spectrum access decisions.

Optimizing the period of Spectrum Sensing: The spectrum sensing result will be more accurate if the observation period of the spectrum sensing is long. Also, a single radio transmitter receiver cannot transmit in the same frequency band during sensing. One of the drawbacks of longer observation period is decreased throughput (Figure 2.2). An optimal spectrum sensing solution is achieved with optimization of this performance tradeoff. If the accuracy of spectrum sensing is low, it degrades the performances of both licensed and unlicensed users due to collision and interference to the transmissions by licensed users. Convex optimization or similar classical optimization techniques can be used for optimal solution.

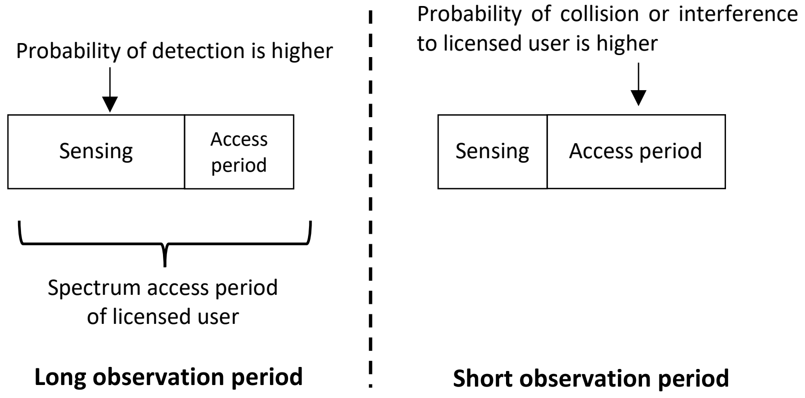


Figure 2.2 Tradeoff between Spectrum Sensing time and user throughput.

Spectrum Sensing in Multichannel Networks: In a cognitive radio network, multichannel transmission like OFDM based transmission is typical. Only few available channels can be sensed simultaneously because the number of available interfaces at the radio transmitter receiver is less than the number of available channels. The performance of the system depends on selection of the channel from all available channels. For spectrum sensing, selecting the occasionally occupied channel by the licensed users is better compared to mostly occupied channels. Under hardware constraints at the cognitive radio transmitter receiver, selection of the channels should be optimized to achieve the optimal system performance for spectrum sensing in a multichannel environment.

2.2 Cognitive Radio Standardization

2.2.1 IEEE SCC 41

It is very much necessary to standardize process, terms and other related issues as there are many technical and economic aspects in efficient spectrum management using software defined radio in a cognitive radio network. For development and implementation of a cognitive radio network, it is required to have standard processes.

Till now all are working independently and therefore the results are incoherent. A central coordination among, organizations, academia and research groups in industry is required as a solution [1]. To initiate series of related standards, the IEEE Standards Coordinating Committee (SCC) 41 on Next Generation Radio and Spectrum Management has been established namely IEEE 1900.

For efficient spectrum management and to solve the issues for developing, implementing and deploying the next generation radio access network, the IEEE SCC 41 was established. There is one study group and four working groups in IEEE SCC 41. For initiating the standardization process for different aspects of a cognitive radio system, the responsibility lies with each group. Each working group will propose the standards in a series for IEEE 1900. Thus, the standards will be applied to gamut of products related to cognitive radio.

The major components of the IEEE 1900 standards are IEEE 1900.1, IEEE 1900.2, IEEE 1900.3, IEEE 1900.4 and IEEE 1900.A. The basic IEEE 1900.1 standard was published on September 26th, 2008. Other standards were published subsequently.

Major functions these standards are related to spectrum management, software-defined radio, Optimization of the operating parameters, coexistence and compliance in the software part, Heterogeneity and dynamic spectrum-access.

In cognitive radio, there is coexistence of many wireless devices and services in the same location at the same time. Optimization of the operating parameters of these devices and services is a crucial issue to manage and avoid interference. The IEEE 1900.2 standard will recommend the criteria for interference analysis.

The next generation wireless systems and cognitive radio i.e. IEEE 802.18,19,21 and 22 can be related to other IEEE projects or standards also. There is a group responsible for participating and monitoring the evolution of the radio regulatory activities in different projects (e.g. for IEEE 802.11 WLAN, IEEE 802.15 WPAN, IEEE 802.16 WMAN, IEEE 802.20 Mobile WMAN, and IEEE 802.22 WRAN). This radio regulatory advisory group is IEEE 802.18. For any demand for spectrum access, this group may recommend to the regulators and other parties after making proper comments. There is another group for coexistence of technical advisory group the IEEE 802.19. The main function of this group is to solve the issues of coexistence between unlicensed wireless networks based on IEEE 802 standards (e.g. IEEE 802.11 and Bluetooth). Whenever a new standard for an unlicensed wireless network is introduced, this group will check the coexistence of that standard. Also, it will ensure that new standard will exist along with other existing technologies operating in the same spectrum. For seamless mobility management (handoff) for both homogenous and heterogeneous wireless technologies, the IEEE 802.21 is the new standard to support this. The next generation wireless systems will enjoy the fundamental standard in which a mobile user can use multiple wireless technologies concurrently.

The IEEE Standards Coordinating Committee (SCC) 41 on Next Generation Radio and Spectrum Management has been established to initiate a series of standards, namely, IEEE 1900. This IEEE Standards Coordinating Committee will develop standards related to dynamic spectrum access networks. The focus is on optimum use of the spectrum.

New techniques and methods of dynamic spectrum access require managing interference, coordination of wireless technologies and include network management and information sharing. Dynamic Spectrum Access (DSA) is the time adjustment of Spectrum Utilization in response to changing environment.

IEEE 802.22 WRAN covers large area for data communication [65]. TV band are largely unoccupied. So, this technology will operate on TV bands. IEEE 802.22 uses dynamic spectrum access so that these devices do not interfere with incumbent service users.

2.2.2 IEEE 802.22 for Wireless Regional Area Networks (WRANs)

From observation, it is noted that TV bands are not occupied in many regions' majority of the time. For data communication these 6 MHz bands are very suitable. TV bands operate on low frequency band. This band of operation is 54-862 MHz in North America and 41-910 MHz in other parts of the globe. Due to its operation on low frequency, it is more suitable for long range communication. IEEE 802.22 system reuses the unoccupied TV band and this standard is proposed to support mobile users in a cell with 100 km range. To avoid interference to TV service users, the cognitive radio concept is applied [66] [67].

The architecture of WRAN is very similar to IEEE 802.16 WiMAX. IEEE 802.22 WRAN is a point to multipoint network. All the connections from Consumer Premise Equipment (CPEs) are controlled by the Base Station (BS). Spectrum access by all CPEs is decided by BS. Also, the allocation of transmission burst to all CPEs in both uplink and downlink is decided by the BS. In case of additional coverage are requirements, relay base stations are deployed [68].

2.3 Open Research Issues in IEEE 802.22

Open research issues in IEEE 802.22 networks are summarized as below:

• **Coexistence with Incumbent Service:** In band channel sensing is must to avoid the interference with licensed users. Consumer Premise Equipment (CPE) must continuously sense the in-band channel and report to the BS regarding status of the channel. Based on this information, BS prepares a map of spectrum status and optimal channels are allocated for communications to all CPEs. To maximize the use of spectrum opportunities, efficient channel sensing mechanisms is to be developed with low signaling overhead.

• **Self-Coexistence: S**ometimes there is competition and cooperation among IEEE 802.22 network service providers. The number of unused TV bands is also limited. In this case, to avoid interference to each other, IEEE 802.22 networks require a careful channel access scheme when all these networks coexist in the same or overlapping area. Self-coexistence means all these networks may have competition or cooperation with each other. For this, network performance analysis models along with its efficient methods for self-coexistence should be developed.

• **Economic Models and Pricing:** For implementation of IEEE 802.22 WRAN system, development of economic models and pricing is necessary. This is required because WRAN will use bands which are allotted to TV service providers. These TV service providers are owner of that band. Owners have to give right to WRAN user to access their bands. With appropriate economic models and pricing, the optimal number of TV bands to be traded. Also, optimal price of TV band can be obtained.

• **QoS Support:** One more open research issue is to develop a QoS framework for supporting various traffic types including real time, constant bit rate or best effort traffic in IEEE 802.22 networks. In this case, to support dynamic and opportunistic channel access, design of traffic scheduling, admission control and resource allocation in the QoS framework is necessary in 802.22 networks.

2.4 State of the Art

The Wireless Technology has witnessed tremendous advancement in recent times. The users are increasing day by day and hence the wireless network is high in demand. There has been increase in demand for additional radio spectrum for wireless technology. This is due to requirement of large bandwidth for high speed data services. The scarcity of radio spectrum has become a challenge for the conventional fixed spectrum assignment assigned by Federal Communication Commission (FCC) [69].

In the field of wireless communication, for optimum utilization of Radio Frequency (RF) spectrum, the Cognitive Radio (CR) is a new paradigm. When the channel is not accessed by primary user (PR), the cognitive radio (CR) will be allowed to use the spectrum to communicate with the other CRs. The principle task of the cognitive radio is spectrum sensing. Through the spectrum sending, the CR accurately determines the licensed users' existence (signal). It also identifies the available vacant spectrum.

The detection performance of cognitive radio user can be improved and in order to improve this, the Jaya Algorithm based cooperative spectrum sensing is proposed. This algorithm also helps in reducing the probability of error.

2.5 Literature Review

Hussien et. al. [70] has implemented an approach where using wavelet-based detection, the wideband spectrum sensing is investigated. For collaborative wavelet base detection, a new system model is proposed and simulated. The results of simulation demonstrated that there is improvement in edge detection performance due to collaboration between SU. Also, better detection is achieved at higher average SNR level of the primary user, when it occupies, the wideband spectrum. Testing of performance of three fusion rules OR, AND and MAJORITY was carried out. A more accurate edge detection was achieved through the AND Combining. However higher protection for primary user was provided by OR-combining. This is because the edges are captured even at low average

SNR level. In OR-combining the number of detected edges is the highest among the three fusion rules investigated. Due to this more processing is required in OR-combining to decide the number and locations of sub bands within the wideband spectrum.

Keraliya et.al. [71] have proposed Teaching Learning Based Optimization (TLBO) algorithms based cooperative spectrum sensing. Result of probability of error is shown with different values of λ using TLBO. Also, conventional hard decision and soft decision fusion techniques like AND OR MAJORITY and soft decision fusion techniques like EGC are used. Some of the design parameters used are: Time Bandwidth Product TW=5, Rayleigh channel is considered and 2u number of received samples is considered. For TLBO, they considered 50 iterations and 15 number of particles. There is also one assumption that all reporting channels are ideal and they do not give any false reporting to Fusion Center.

It is also shown that minimum probability of error (Pe) for cognitive radio system is achieved by using TLBO based optimization. It generated the best weighting coefficient vectors. But after simulation, it is proved that conventional Hard Decision Fusion (HDF) schemes does not give good error performance. This is due to of low data fusion decision from Secondary User in the whole network.

A typical case of $\lambda = 6$ is taken for the convergence performance of TLBO. After the simulation, they got convergence of probability of error in just 30 iterations. It shows that TLBO can meet the real time requirement of cooperative spectrum sensing for cognitive radio. As it is so fast, it reduces computational complexity too. For probability of detection this standard deviation under 25 simulations is negligible. This shows that the TLBO based optimization is very stable.

Rao et. al. [72] proposes an elitist based self-adaptive multi population Jaya Algorithm. The results of the proposed algorithm are tested on small as well as large scale unconstrained and constrained benchmark problems in addition to the computationally expensive problems of the CEC 2015. In order to find the average rank of the algorithm, the Friedman rank test is used. Also, it is observed that the proposed algorithm is superior than the other algorithms. Also, for the design optimization problems of a micro channel heat sink, the proposed method is used.

Multi population search scheme is used in the proposed method for enhancing the search mechanism of the Jaya Algorithm, which divides the population into a number of subpopulations adaptively. Easy integration of subpopulation-based scheme with single population based advanced optimization algorithm can be achieved. The results of SAMPE-Jaya for the benchmark problems are found better as compared to the latest reported methods which are used for optimization of the same problems. In the case of MCHS, while using the proposed SAMPE-Jaya algorithm, better parent optimal solutions are obtained as compared to those hybrid MOEA, numerical analysis, TLBO and Jaya algorithms.

The concept of SAMPE-Jaya Algorithm is simple. Also, it is not having any algorithmic specific parameters to be tuned. Hence implementation is easy on engineering problems, where problems are usually complicated with a number of design parameters plus having discontinuity in objective function.

Yucek et.al [63] have provided a survey of spectrum sensing algorithm for cognitive radio applications. The spectrum is a precious resource in wireless communication systems, it has been core for research and development efforts over the last ten years. Cognitive Radio is one of the efforts, to utilize the available spectrum more efficiently. Cognitive Radio use the available spectrum opportunistically. CR has become an exciting and promising concept.

Sensing the available spectrum opportunities is one of the main tasks of cognitive radio. In this paper, by considering different dimensions of the spectrum space, re-evaluation of the spectrum opportunity and spectrum sensing concepts are done. While solving some of the traditional problems, new opportunities and challenges for spectrum sensing are created through the new interpretation of spectrum space. The study also explains different parameters of the spectrum sensing task. Various sensing methods are discussed. It is also shown that the cooperative spectrum sensing is the solution to some common problems in spectrum sensing. Discussion of proactive approaches and sensing methods used in current wireless systems are also given. Some of the open research areas which can be considered are estimation of spectrum use in different dimensions which includes time, frequency, space, angle and code, identifying possibilities in these dimensions and evolving algorithms for prediction into the future using this information.

Rao et. Al. presented [73] [74] [75] [76] a novel optimization method, Teaching Learning Based Optimization (TLBO). This is based on the philosophy of the teaching-learning process. And its performance is checked by experimenting with different benchmark problems with different characteristics. The effectiveness of TLBO for different performance criteria such as success rate, mean solution, average number of function evaluations required, convergence rate is also checked. A better performance of TLBO over other nature inspired optimization methods for the constrained benchmark functions is shown in the results. Moreover, a better performance with less computational effort for large scale problems, i.e. problems of a high dimensionality is also shown by TLBO. This method can be used for the optimization of engineering design applications.

LA Mpiana et. al. [77] proposed a spectrum sensing algorithm. This is based on channel characteristics. The purpose is to have a selection of the best available spectrum by evaluating the channel characteristics responding to the secondary user needs. The effective collaboration of the spectrum management and the secondary user to match the user requirements, is achieved through this. They have worked more on constant parameters. Mainly to determine the quality of service for the spectrum selection.

J. Shen et. al. [78] took into consideration the optimal strategy of Cooperative Spectrum Sensing (CSS) using a counting rule and made three contributions as follows:

(i) They proved that the ROC (P_d vs P_f) of the energy detector is concave under fading environments.

(ii) They analyzed the randomization at the center and proved that the non-randomized rules are locally optimal for Independent and Identically Distributed (iid)

(iii) The optimal counting rule under both the Neyman-Pearson and Bayesian Criterion was derived. In addition to this, to calculate the optimal settings, simple algorithms are introduced. Under both Neyman-Pearson and Bayesian criteria, it is proved that the optimal counting rule is significantly preferable to non-optimal rules.

Edward C. Y. Peh et. al. [79] [80] discussed the optimal decision fusion rule for the sensing throughput tradeoff design in a cognitive radio network. The secondary user has different SNR levels and threshold values. Based on likelihood ration test, the optimal decision fusion rule is a weighted rule.

Discussion happened on various proposed methods to compute the secondary users' thresholds, their decisions' weightings and the threshold of the fusion rule under various scenarios. If the individual secondary users' thresholds are optimized using a centralized processor, then the throughput is the highest. There is loss in the throughput, if the secondary users' thresholds are constrained to be the same. But the loss is reduced if the threshold is set at a level such that the secondary users with high SNRs operate near their optimal thresholds while letting the secondary users with low SNRs lose their optimality.

To set the individual secondary users' thresholds in a distributed manner, without the knowledge of each other's channel information, two methods are proposed. Discussion on the characteristics of the decisions' weightings between secondary users with high SNRs and low SNRs are also done.

Summary: After literature review, it is found that optimization algorithms are not applied much in the field of spectrum sensing in cognitive radio. An algorithm specific parameter less algorithm can give the optimal solution in a smaller number of iterations with low complexity. Application of TLBO algorithm for optimization is found in only one paper from the literature review [71]. JAYA algorithm is an advanced algorithm specific parameter less algorithm developed by Prof. Rao in 2016 [72]. This algorithm is applied for optimization in mechanical engineering problems. But application of JAYA algorithm is not found anywhere in the literature for communication field. JAYA algorithm performs better than TLBO in terms of number of iterations as well as complexity [81]. So, in this work, JAYA algorithm is applied for optimization of probability of error in spectrum sensing for cognitive radio.

2.6 Definition of the Problem

This research work is carried out to apply the energy detection spectrum sensing technique to find the free spectrum for secondary users. Primary Users have the first priority to use their spectrum and when that spectrum is not in use by Primary Users, Secondary users can utilize it.

But when PU wants that spectrum again, SU has to make that spectrum vacant and it has to switch over to another free spectrum.

So, this research work is carried out to find free spectrum, apply optimization algorithm to find optimal solution for minimum probability of error and to select the best spectrum among available free spectrums by applying optimization algorithm.

2.7 Research Objectives

- To Minimize Probability of Error in spectrum sensing.
- To find lowest probability of error in minimum number of iterations.
- To select the best spectrum among various available spectrums.

CHAPTER-3

Spectrum Sensing Techniques and Optimization Algorithms

3.1 Spectrum Sensing Methods

The Wireless Technology has witnessed tremendous advancement in recent times. The users are increasing day by day and hence the wireless network is high in demand. There has been increase in demand for additional radio spectrum for wireless technology. This is due to requirement of large bandwidth for high speed data services. The scarcity of radio spectrum has become a challenge for the conventional fixed spectrum assignment assigned by Federal Communication Commission. In the field of Wireless Communication, for efficient utilization of Radio Frequency (RF) spectrum, the Cognitive Radio (CR) is a new paradigm. When the channel is not accessed by primary user (PR), the cognitive radio (CR) will be allowed to use the spectrum to communicate with the other CRs [23] [82]. The principle task of the cognitive radio is spectrum sensing. Through the spectrum sensing, the CR accurately determines the licensed users' existence (signal). It also identifies the available vacant spectrum. In this section various spectrum sending techniques are discussed.

3.1.1 Energy Detector

Because of its low implementation complexities, the energy detector-based technique, also named as radiometry or periodogram [83] [84] [85] [86] , is widely used spectrum sensing technique. The receivers do not require any knowledge of the primary users' signal in this Energy Detector based sensing. The detection of the signal is done by comparison of the output of the energy detector with a threshold that is dependent on the noise floor.

To implement Energy Detection method with improved signal to noise ratio, the squaring and cubing operations have been used [87] [88] [89].

Energy Detection (ED) is popular because it is easy to implement and does not require any previous details about the primary signal. It selects the presence or absence of the primary signal based on the energy of the detected signal. It does not need any previous knowledge of the primary signal; hence the ED method can be implemented to the variation of the primary signal. It has less complexity and does not involve complex signal processing. It is mainly suitable for wide band spectrum sensing.

The energy of the filtered received signal calculated over the time interval T, is the output of the integrator. It is measured as the test statistic to test the two hypotheses H_0 and $H_{1.}$ Here the H_0 denotes the absence of the primary signal and presence of only noise. The H_1 denotes the presence of both primary signal and noise. Hence for two hypotheses three numbers of important cases are

a) P (HI / HI) - If primary user is present then H_I turns out to be TRUE in case of presence of primary user is called as Probability of Detection (P_d).

b) P (H_O / H_I) - If primary user is present then H_O turns out to be TRUE i.e. P (H_O / H_I) is called as Probability of Missed-Detection (Pm).

c) P (H_I / H_O) - If primary user is absent then H_I turns out to be TRUE is called as Probability of False Alarm (P_f).

The energy detection method is easy in implementation. Because it does not need the previous knowledge about the primary signal. It calculates the energy of the input signal then compares with a threshold value. If signal value found is more than energy level of threshold then primary signal is present as shown in the flow chart below.

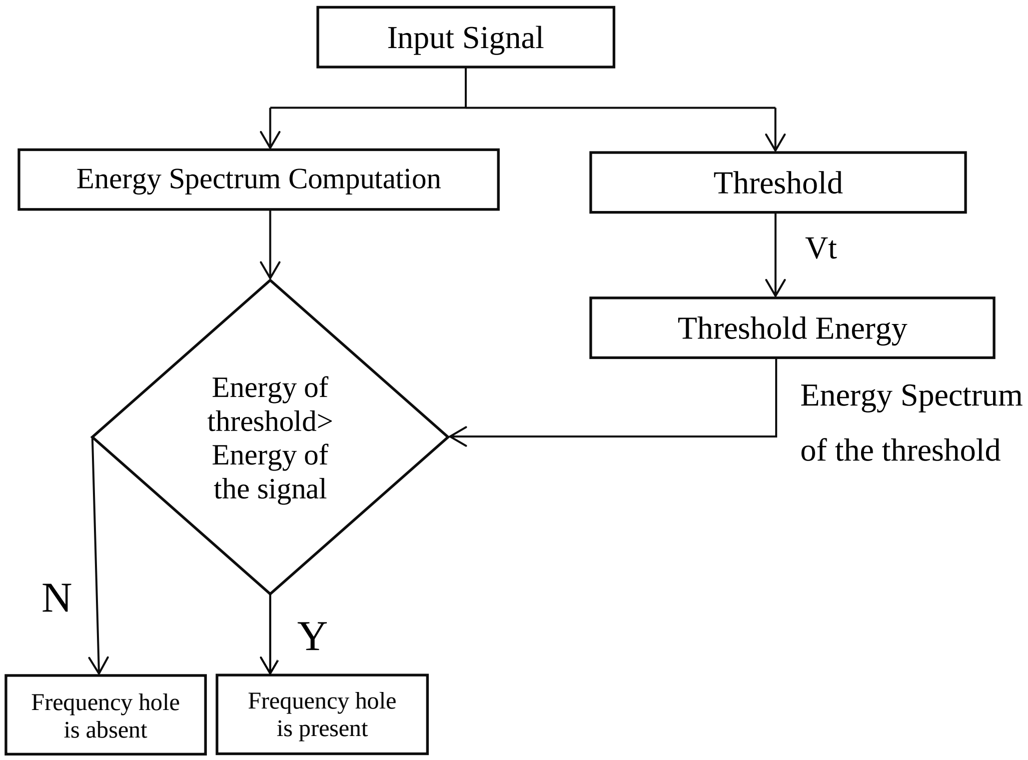


Figure 3.1 Flowchart of Energy Detection Method

3.1.2 Cyclostationary Detection

In this technique of cyclo-stationarity feature detection for spectrum sensing, by examining cyclo-stationary features of the received signal, PU's transmission is detected [90] [91]. For any signal, cyclo-stationary features are caused by the periodicity or its statistics like auto correlation and mean. Also, to perform spectrum sensing, periodicity is intentionally induced. In this spectrum sensing technique, cyclic correlation function is used instead of power spectral density (PSD) to detect presence of primary user in a given spectrum. The cyclo-stationarity based detection technique differentiate primary user's signal from noise signal [92] [93].

It is the fact that modulated signals are cyclo-stationary and it has spectral correlation because of the redundancy of signal periodicities while noise is wide sense stationary

(WSS) with no correlation. In addition to this, cyclo-stationarity feature differentiates various types of transmissions and primary users. This spectrum sensing technique exploits the periodicity in the received signal to confirm the presence of primary users. At low signal to noise ratio (SNR) condition, cyclo-stationary feature detection technique outperforms the energy detection-based spectrum sensing technique [94].

3.1.3 Waveform Based Sensing

In wireless systems, known patterns are used to support synchronization as well as for other communication tasks, these patterns are regularly transmitted pilot patterns, preambles, mid-ambles, spreading sequences etc. a sequence transmitted before each burst is known as preamble and a sequence transmitted in the middle of a burst of slot is known as mid-amble. If the known pattern is present, the received signal is correlated with a known copy of itself to perform spectrum sensing. This method of spectrum sensing is known as waveform based sensing or coherent sensing and it is applicable only to the systems where known signal patterns are available. In terms of reliability and convergence time, waveform-based sensing technique is better than detector-based technique.

In addition to this, performance of waveform-based sensing can be further increased with increase in the length of the known signal pattern.

3.1.4 Radio Identification

If the transmission technology used by primary users is identified, a whole knowledge about the spectrum characteristics can be attained. CR can have higher dimensional knowledge and higher accuracy by such identification of PU’s transmission technology.as an assumption, let PU’s transmission technology be identified as Bluetooth Signal. The range of the Bluetooth signal is known to be around 10 meters. This information can be used by CR to extract some useful information in space dimension. Also, in some applications, CR may want to communicate with the identified communication systems.

There are two techniques used for radio identification (1) Feature Extraction (2) Classification Techniques. The goal of these techniques is to identify the known transmission technologies and also to achieve communication between them.

In Radio Identification based spectrum sensing the most probable PU's technology is selected by extraction of several features from the received signal.

3.1.5 Match Filtering

When the transmitted signal is known, match filtering is the optimum method for primary user detection, in cognitive radio. As compared to other spectrum sensing techniques match filtering requires minimum time to achieve a particular value of probability of miss detection (PM) or probability of false alarm (PFA) [95].

In addition to these there are many other spectrum sensing techniques found in literature [96] [97].

3.2 Optimization Methods

The temporally idle spectrum, which is called spectrum hole or white space is found by the CR user through spectrum sensing. When the licensed user wants to transmit then cognitive user has to use another available spectrum or user has to change its transmission parameter in order to avoid interference.

There are many optimization techniques which are used to find the optimal solution for improvement in performance of spectrum sensing. These techniques optimize the parameters so they are as per required maximum and minimum criterion [98].

Optimization techniques like Genetic Algorithm (GA), Particle Swarm Optimization (PSO) [99], Ant Colony Optimization (ACO) and Teaching Learning Based Optimization (TLBO) are discussed in this section to meet the user's Quality of Service (QoS) needs in the Cognitive Radio [100].

3.2.1 Genetic Algorithm

The basic purpose of Genetic Algorithm (GA) is designed for simulation processes of evolution [101] [102]. The evolution is the process of optimization. This algorithm follows the survival of the fittest principle. This is used where the search space is large and it is not possible to be effectively solved by classical or conventional optimization method. The difference from classical method is that, in this method the series of a solution called population is used to the objective function, instead of making a single solution [103].

Initial population made of from different feasible solution is given. The optimization algorithm searches the best chromosomes and the un-fits are rejected from the given population. A fitness score is evaluated which is generated by means of maximization of objective function. This score finds the generation most appropriate for surviving to the future generation. The generation giving the highest score is nominated for surviving. Successive generations are given by the steps below:

- Selection
- Crossover
- Mutation

Crossover and Mutation are repetitively used most of the time. This evaluation and generation are done iteratively in order to raise the proportion of fit members. As soon as the stop criteria are satisfied through the number of iteration or achieved through some predefined fitness, then the algorithm stops. The resultant value gives optimal solution. The following figure 3.2 shows the flowchart of GA.

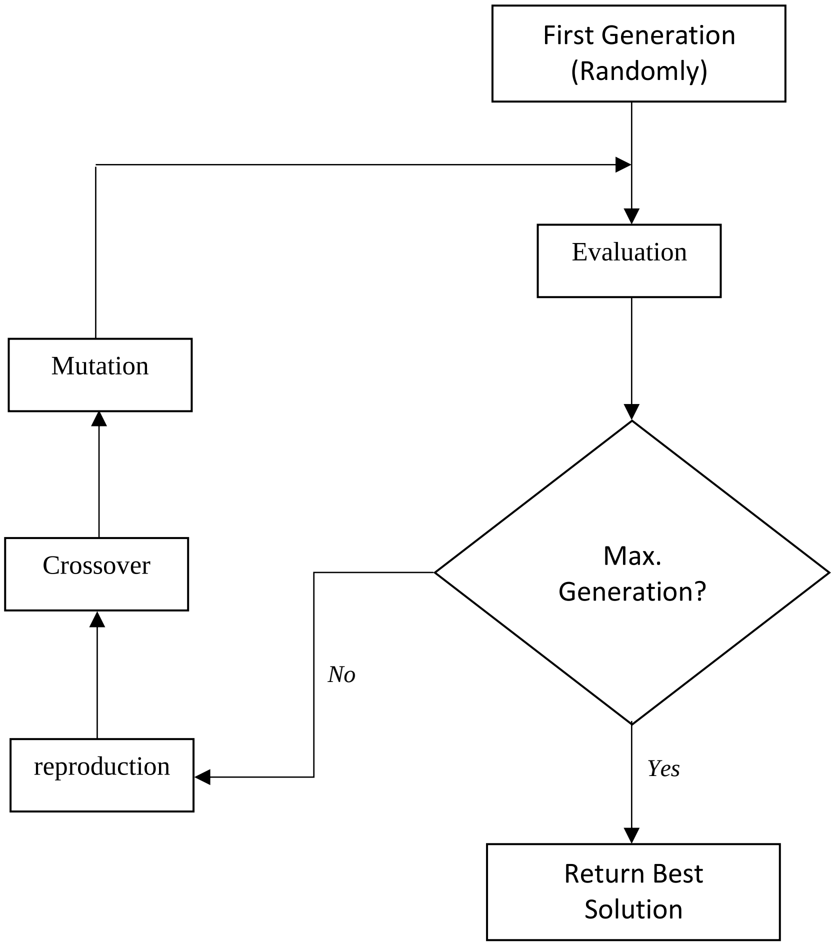


Figure 3.2 Flow chart of Genetic Algorithm

3.2.2 Ant Colony Optimization

The algorithm Ant Colony Optimization (ACO) was derived from the ants moving for finding the food sources [104]. In this algorithm, the ants find the food and take back to their nest. A substance called pheromones is left by the ants when they are going back to nest. According to the amount and quantity of the food sources, the amount of pheromone is placed. This pheromone gives guidance of path to other ants to the food. The path where the pheromone is larger is followed by other ants.

There are three main functions of ACO optimization method as shown below. The flowchart is shown in Figure 3.3.

1. Auto Solution Construct

2. Pheromone Update

3. Daemon Action

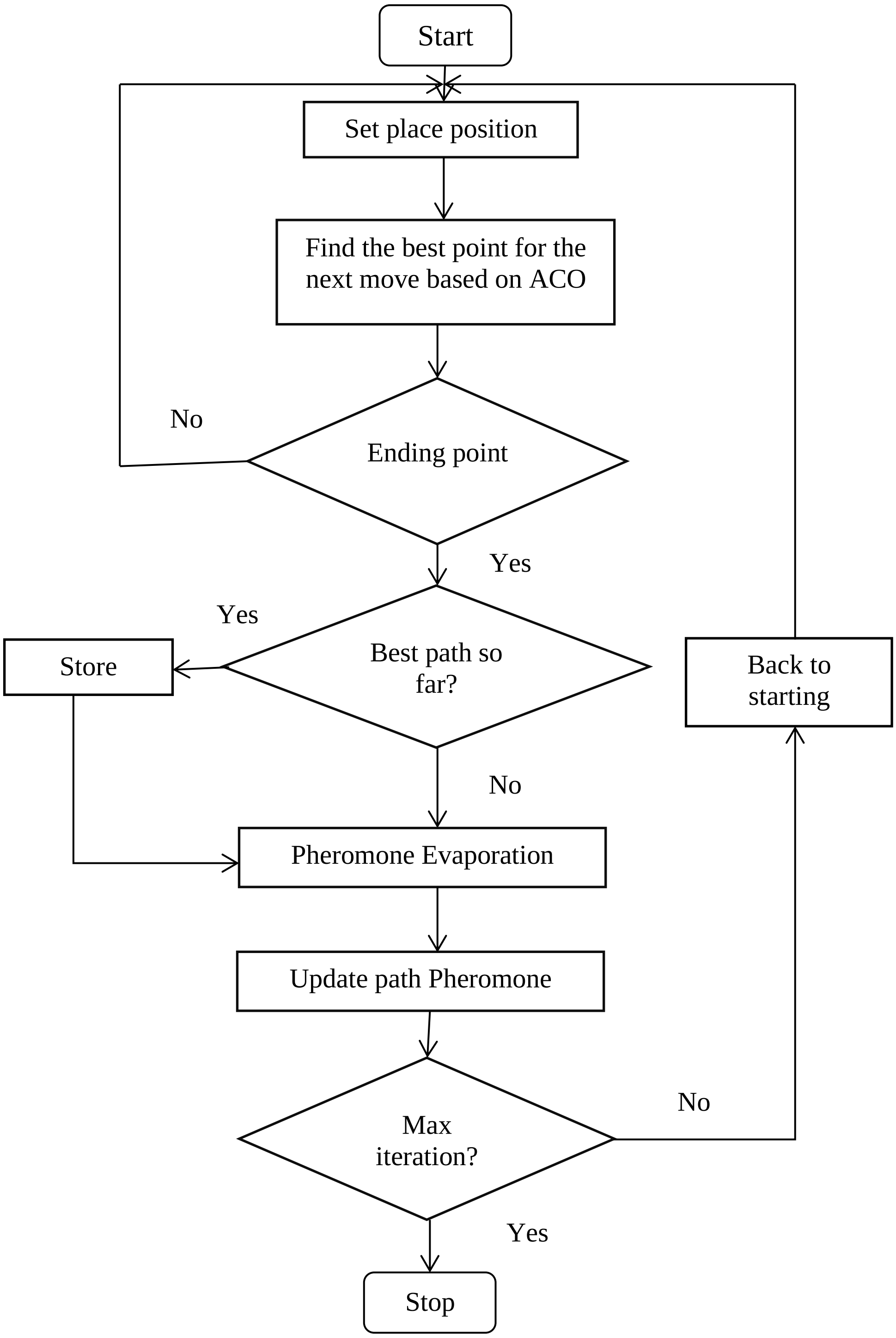


Figure 3.3 Flow chart of ACO

3.2.3 Particle Swarm Optimization

Particle Swarm Optimization (PSO) technique is inspired by the behavior of bird or fish to find their food [105] [106]. It is a population-based technique for optimization. Design of this algorithm depends on the behavior of a bird/particle. In searching of food, a bird which is nearer to food chirps loudly so that other birds follow it. In this process, if some other bird is nearer to the food compared to previous bird, it chirps loudly and all birds follow this new bird. This is the way to find the objective (food). Each particle tries to get the best optimal solution. They achieve this from the past experiences. Particle Swarm Optimization algorithm is having high converge capability, it is simple and easier to implement [107] [108].

Particle Swarm Optimization algorithm has two different equations. One is for the velocity of the particle and other is for the position of the particle. At the end of each iteration, the value of position and velocity changes till the termination criterion is satisfied [109].

3.2.4 Teaching Learning Based Optimization

The following are the limitations associated with classical (conventional) optimization methods [73]:

- Conventional methods depend on the nature of variables (i.e. linear or nonlinear) of optimization problem
- Most of the conventional methods end to a sub optimal point.
- Classical or conventional methods do not give Generic Solution.
- The efficiency of conventional method depends on variable size, feasible solution size and also constraint in the optimization problem [76].
- Parallel machine problems cannot be solved by classical methods
- Conventional methods depend on the class of constraint functions (i.e. linear or nonlinear)

Due to limitations associated with classical methods, Rao et al proposed Teaching–Learning-Based Optimization (TLBO) method [73]. It is an advanced method for optimization. It is based on the impact of a teacher on the performance of learners. The performance of student can be in the form of marks, reward or grade. Like other nature-inspired algorithms, TLBO is also a population-based method and uses a population of solutions to proceed to the global solution. A teacher shares his knowledge with students in a classroom. The student's grade or marks is the reflection of teacher's performance. It is obvious that a good teacher trains student such that students can have better results in terms of their marks or grades. The terminology of TLBO algorithm is related by:

- Population = Class or Group of Students
- Design variables = Subjects
- Fitness value= Learner's result.

The working of TLBO process has two phases: (1) Teacher Phase (2) Learner Phase.

The 'Learner Phase' is about the learning through the mutual communication between learners and the 'Teacher Phase' is about the learning from the teacher. The flow chart is shown in Figure 3.4

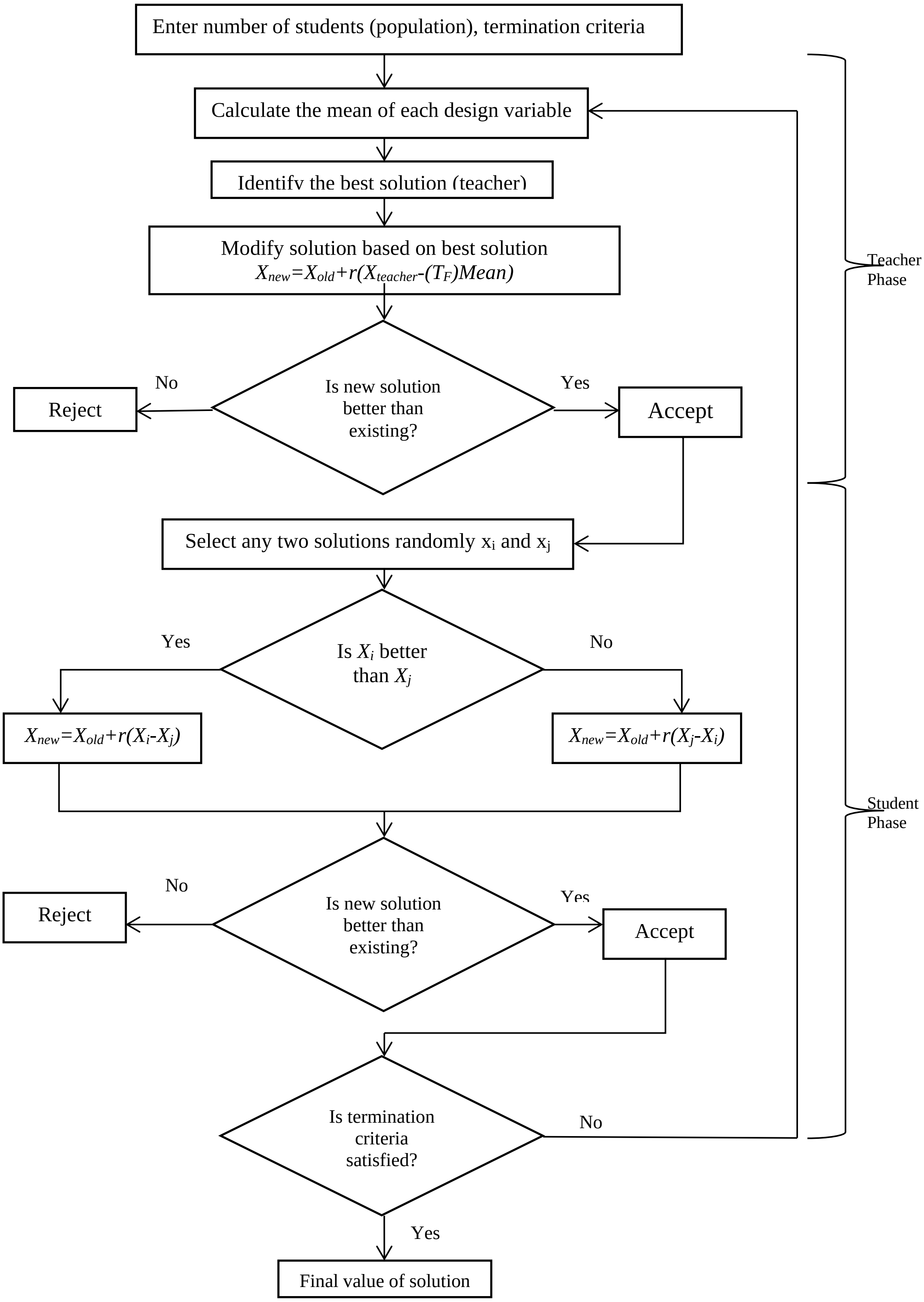


Figure 3.4 Flow chart of TLBO

TLBO algorithm is further explained by following optimization problem.

The objective is to find the value of x_1 and x_2 so that the following function is minimized.

Objective function: Unconstrained Himmelblau function

$$\min f(x) = (x_1^2 + x_2 - 11)^2 + (x_1 + x_2^2 - 7)^2 \tag{3.2.1}$$

Subject to $-5 \leq x1, x_2 \leq 5$

Table 3.1 Initial Population for TLBO Algorithm

Learner	x_1	x_2	f(x)
1	3.2	0.4	13.3792
2	0.2	2.3	77.2757
3	3.2	0.3	13.9757
4	1.6	4.6	263.1232
5	2.2	0.8	46.0352
Mean	**2.08**	**1.68**	

In this algorithm the minimum value of f(x) is considered as the best learner who is the teacher. The mean value is improved through the effort of the teacher. We assume r_1=0.25, r_2=0.43 for x_1 and x_2 respectively.

The differences of mean for these two variables are calculated by:

$$\text{diff}\ (x_1) = 025 * (3.2 - 2.08) = 0.28$$

$$\text{diff}\ (x_2) = 0.43 * (0.4 - 1.68) = -0.55$$

These differences of mean are added to x_1 and x_2 for all values in respective columns of table 3.1. Table 3.2 shows these new values of x_1, x_2 and the respective values of the objective functions.

Table 3.2 Teacher Phase: New values of the objective function

Learner	x_1	x_2	f(x)
1	3.480	-0.150	13.154
2	0.480	1.750	93.307
3	3.480	-0.250	12.694
4	1.880	4.050	138.961
5	2.480	0.250	41.025

These values of objective function of Table 3.1 and Table 3.2 are compared and the minimum value (best value) of f(x) are put in Table 3.3. Here, The teacher phase ends for the TLBO algorithm.

Table 3.3 Updated values of objective function for teacher phase

Learner	x_1	x_2	f(x)
1	3.480	-0.150	13.154
2	0.200	2.300	77.275
3	3.480	-0.250	12.694
4	1.880	4.050	138.961
5	2.480	0.250	41.025

Here, in the learner phase, any learner will interact randomly with other student through formal communication, group discussion, presentation, etc. After interactions, values of x_1 and x_2 for learner are updated as shown in Table 3.4.

Considering r_1=0.46, r_2=0.32 for x_1 and x_2 respectively. These new values of x_1 and x_2 are estimated by following.

After the interaction between learner 1 and learner 2, the transfer of knowledge from learner 1 to learner 2 occurs because the value of objective function is better for learner 1 than learner 2. This new values of x_1 and x_2 for the case of learner 1 are estimated as,

x_1 (for learner 1) = 3.48 + 0.46 (3.48-0.2) = 4.988

x_2 (for learner 1) = -0.15+0.32 (-0.15-2.3) = -0.934

In similar way, after the interaction between learner 2 and learner 5, the knowledge is transferred from learner 5 to learner 2 because the value of objective function is better for learner 5 than learner 2. This updated new values of x_1 and x_2 for the case of learner 2 are calculated as:

x_1 (for learner 2) = 0.2 + 0.46 (2.48-0.2) = 1.2488

x_2 (for learner 2) = 2.3 + 0.32 (0.25-2.3) = 1.644

Table 3.4: Updated values of the objective function for learner phase

x_1	x_2	f(x)	Iterations
4.988	-0.9340	169.106	1 and 2
1.248	1.6440	70.078	2 and 5
3.4800	-0.2820	12.523	3 and 1
2.1560	2.8340	22.534	4 and 5
2.7560	-0.9660	30.062	5 and 4

These values of objective function of Table 3.3 and Table 3.4 are compared and minimum value (best value) of objective function is placed in Table 3.5. Here, the learner phase ends for the Teaching Learning Based Optimization algorithm.

Table 3.5: Updated values of the objective function for learner phase

Learner	x_1	x_2	f(x)
1	3.480	-0.1500	13.1548
2	1.248	1.6440	70.0785
3	3.480	-0.2820	12.5231
4	2.1560	2.8340	22.5344
5	2.7560	-0.9660	30.0626

After single iteration, value of the objective function goes down from 13.3792 to 12.5231. It will further slowdown through a greater number of iterations.

TLBO is applied in various fields for optimization [110] [111] [112].

CHAPTER-4

Proposed Methodology

4.1 Introduction

In literature, use of Jaya algorithm is not found for optimization in the field of spectrum sensing. The concept of the Jaya algorithm is that the solution obtained for given problem moves towards the best solution and avoids the worst solution. This algorithm does not require any algorithm-specific control parameters, it requires only the common control parameters.

In our research work, the value of Probability of Error 0.23 at threshold value of 8 in just 16 iterations is obtained by using Jaya Algorithm.

In this research work, Energy detection technique in cooperative manner is used for spectrum sensing and an advanced optimization technique Jaya algorithm is applied to get the minimum Probability of Error.

In addition to this, the best spectrum for secondary users from various available spectrums is selected using Analytic Hierarchy Process (AHP) as well as using combination of AHP and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods.

4.2 Cooperative Spectrum Sensing (CSS)

Due to multipath propagation of the signal, output of local spectrum sensing decreases. It happens due to the occurrence of wireless propagation characteristics like fading and shadowing. One of the drawbacks of such type of wireless channel state is hidden node. In hidden node problem, cognitive transceiver is at distance from primary user but nearer to the primary receiver. So, it generates disturbance. Cooperative spectrum sensing helps in solving these issues. The cooperative spectrum sensing works under the principle of cooperation between adjacent secondary user's spectrum sensing with signal transmission of primary user. They both share local sensing observations and then final decision is taken [113] [114].

Centralized and distributed are the two methodologies for implementation of CSS. [115] [116] [117] [118] [119]. Figure 4.1 describes centralized CSS. In order to detect the channels for the Primary User signal, N number of Secondary Users cooperate with them. Secondary users use reporting channels to send the sensing information to Fusion Centre. These channels are bandwidth limited channels. After getting sensing information from secondary users, FC takes the decision about primary user's presence. This arrangement is effective because all the channels cannot be under high fading environment simultaneously.

The effects of multipath fading through the cooperative diversity is reduced through cooperative spectrum detection. [120], [121], [44], [122]. Also, the effect of hidden node problem is reduced through cooperative spectrum detection.

There are various advantages of cooperative spectrum sensing. They are enlarged coverage, improvement of performance of detector, toughness to non-ideality and the design of detector becomes easier. Hence cooperative spectrum sensing is very important in cognitive radio literature. Detailed reference of CSS can be found in [123], [63], [124], [44], [119], [125], [126] , which includes related problems, other details of CSS and various literature.

Table 4.1 mentions the pros and cons of local versus cooperative sensing schemes.

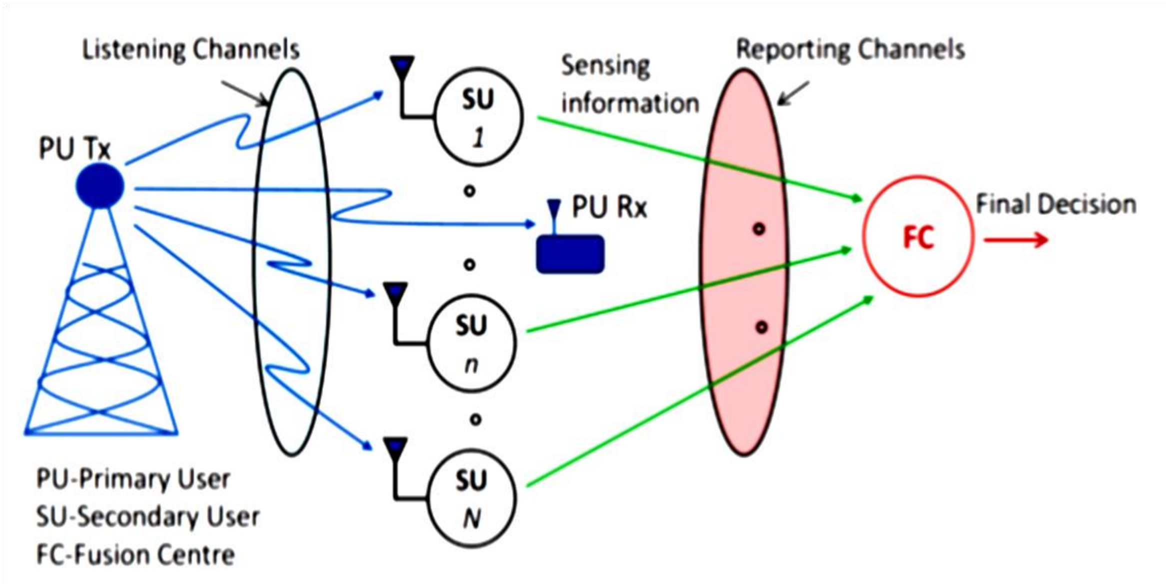


Figure 4.1 Cooperative Spectrum Sensing in a Cognitive Radio Network

4.2.1 Comparison of Cooperative Spectrum Sensing and Local Sensing

Table 4.1 Comparison of Cooperative Spectrum Sensing and Local Sensing

Sensing Scheme	Advantages	Disadvantages
Local Sensing	Computational and Implementation simplicity	Hidden Node problem
		Multipath and shadowing
Cooperative Spectrum Sensing (CSS)	Higher Accuracy	Complexity
	Reduced Sensing Time	Overhead
	Overcome Hidden Node Problems	Requirement of Control Channel

For cooperative spectrum sensing, if energy detection technique is used, then the cooperative nodes send the sensing observations through channels which are reporting to fusion center. This is done through Soft Decision Fusion (SDF) or Hard Decision Fusion (HDF) [127] [128]. Each cooperative node behaves differently in SDF and HDF. In SDF, it provides their exact information for Primary user to FC. It is not taking any decision itself and the Fusion Center decides that primary user signal is present or not.

While in HDF, cooperative nodes are taking its own decision for primary user transmission and send the decision in form of 1 bit to FC.

Based on logic i.e. AND, OR, MINORITY the Fusion Center decides the presence or absence of primary user signal.

4.2.2 Data Fusion Schemes for CSS

There are few issues of spectrum sensing. One of main issue is the hidden terminal problem. This problem is mainly for the case, when the cognitive radio is in shadow or in deep fade. There are ways to overcome or reduce this issue. One of them is multiple cognitive radios can be worked in cooperation for spectrum sensing through cooperative diversity. Hence the probability of detection of fading environment can be greatly improved through cooperative spectrum sensing [129] [130].

The average probability of false alarm (P_f) is calculated by the Fusion Center (FC) in cooperative spectrum sensing. P_f is the probability of falsely detecting the primary signal when it is actually absent. The probability of detection (P_d) with reference of each CR's probability is also calculated by it. The false alarm probability is given by [131].

$$Q_f = \sum_{k=n}^{N} \binom{N}{k} {P_f}^k (1-P_f)^{N-k} = prob\left\{\frac{H_1}{H_0}\right\} \tag{4.1.1}$$

Also, Detection probability is given by

$$Q_d = \sum_{k=n}^{N} \binom{N}{k} {P_d}^k (1-P_d)^{N-k} = prob\left\{\frac{H_0}{H_1}\right\} \tag{4.1.2}$$

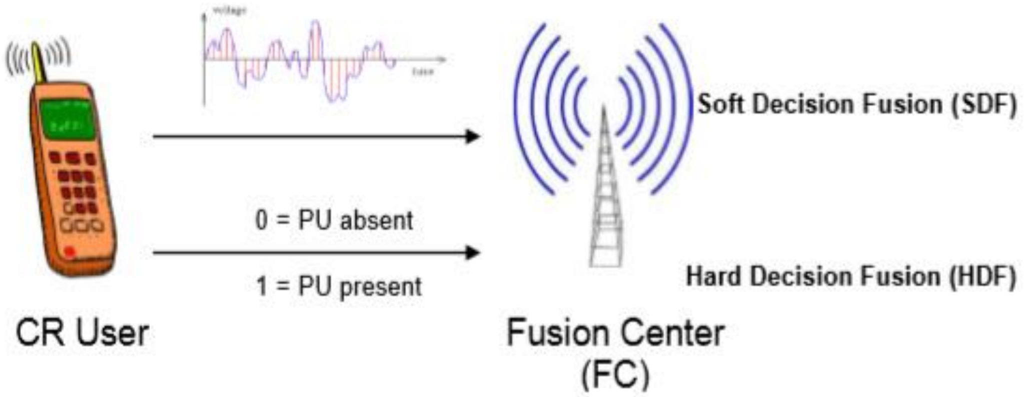


Figure 4.2 Fusion Schemes for CSS

The method of combining locally sensed observations of all secondary users [132] is called fusion scheme in Cooperative Spectrum Sensing.

The two different fusion schemes in CSS as per the types of local sensing observations given to Fusion Center through reporting channels are 1. Data Fusion 2. Decision Fusion.

Data Fusion is known as Soft Decision Fusion (SDF) scheme and Decision Fusion is known as Hard Decision Fusion (HDF). In SDF, Cognitive Radio shares their exact local observations. But in HDF, CR share their individual sensing decisions. Also, in HDF, the local decisions of secondary users decide the final decision at the FC. To get the cooperative decision, a linear combination of all fusion rules at FC is preferable. Such scheme gives low communication overhead. Details on HDF scheme for CSS is given in [133], [134], [119], [80], [135]. OR logic, AND logic and MAJORITY logic are frequently used fusion rules. These are classic cases of the general K out of M rules. Detail of HDF schemes [131] [127]is given below:

AND LOGIC: AND logic works on following principle:

FC makes the decision of PU's presence if all the cooperative nodes for spectrum sensing detect the presence of PU. FC's decision is based on the logic AND of the individual decision of all cognitive users.

The Probability of Detection (P_d) and Probability of False Alarm (P_f) can be calculated by considering k=1 in equation (4.1.1), (4.1.2) respectively.

$$Q_f = \sum_{k=n}^{N} \binom{N}{k} {P_f}^k (1 - P_f)^{N-k} = prob \left\{ \frac{H_1}{H_0} \right\}$$

$$Q_d = \sum_{k=n}^{N} \binom{N}{k} {P_d}^k (1 - P_d)^{N-k} = prob \left\{ \frac{H_0}{H_1} \right\}$$

Putting k=1 in above equations, the Probability of Detection (P_d) and Probability of False Alarm (P_f) can be calculated as below:

$$Q_{d,AND} = P_d^{\ N} \tag{4.1.3}$$

$$Q_{\mathrm{f},AND} = P_f^{\ N} \tag{4.1.4}$$

OR LOGIC: In this scheme the calculation of decision of fusion center is done by logic OR of the individual decision obtained at Fusion Center. The Probability of Detection (P_d) and Probability of False Alarm (P_f) can be calculated by considering k=N in equation (4.1.1), (4.1.2) respectively.

$$Q_f = \sum_{k=n}^{N} \binom{N}{k} {P_f}^k (1 - P_f)^{N-k} = prob\left\{\frac{H_1}{H_0}\right\}$$

$$Q_d = \sum_{k=n}^{N} \binom{N}{k} {P_d}^k (1 - P_d)^{N-k} = prob\left\{\frac{H_0}{H_1}\right\}$$

Putting k=N in above equations, the Probability of Detection (Pd) and Probability of False Alarm (Pf) can be calculated as below:

$$Q_{d,OR} = 1 - (1 - P_d)^N \tag{4.1.5}$$

$$Q_{f,OR} = 1 - (1 - P_f)^N \tag{4.1.6}$$

MAJORITY LOGIC: In this hard decision fusion scheme, the calculation of decision of FC is done by logic AND of the individual decision obtained at FC. Cooperative Probability of Detection (P_d) and Probability of False Alarm (P_f) can be calculated by considering k=N/2 in equation (4.1.1), (4.1.2) respectively.

$$Q_f = \sum_{k=n}^{N} \binom{N}{k} {P_f}^k (1 - P_f)^{N-k} = prob\left\{\frac{H_1}{H_0}\right\}$$

$$Q_d = \sum_{k=n}^{N} \binom{N}{k} {P_d}^k (1 - P_d)^{N-k} = prob\left\{\frac{H_0}{H_1}\right\}$$

Putting k=N/2 in above equations, the Probability of Detection (Pd) and Probability of False Alarm (Pf) can be calculated as below:

$$Q_{d,MAJORITY} = \sum_{K=N/2}^{N} \binom{N}{k} {P_d}^k (1 - P_d)^{N-k} \tag{4.1.7}$$

$$Q_{f,MAJORITY} = \sum_{K=N/2}^{N} \binom{N}{k} {P_f}^{k} (1 - P_f)^{N-k} \qquad (4.1.8)$$

In soft decision fusion (SDF) scheme, CR users do not make any decision, they just forward the exact sensing result to the Fusion center. At FC, appropriate combining rules like EGC of MRC is used for making decision by combining these results from CR users.

SDF gives better results compared to HDF. But it comes with a cost of larger bandwidth requirement for communication of the reporting channel [136] [137] [138]. SDF also generated more overhead compared to HDF.

Equal Gain Combining (EGC):

EGC is the simplest Soft Decision Fusion scheme [139] [140]. Here each secondary user sends its local observation to Fusion Center (FC). At FC, this energy is added together. And finally, comparison is done between collective energy and predefined threshold level. If this collective energy is greater than the threshold value, then FC decides that PU is present, or else it decides that PU is absent. The performance of EGC scheme degrades if the CR user is in deep facing. EGC scheme is shown in figure 4.3. The decision statistic is given by:

$$E_{EGC} = \sum_{k=1}^{N} E_k \qquad (4.1.9)$$

Maximum ratio combining (MRC)

There is a difference in functionality of MRC and EGC. In MRC, a normalized weight is assigned to the sending energy received at FC from each SU before combining them and compare the result with a predefined threshold. Normalized weight to each CR depends on the received signal to noise ratio (SNR).

In Maximum Ratio combining each signal branch is multiplied by a weight factor. It is proportional to the signal amplitude. Therefore, branches with strong signal are further amplified and branches with weak signals are attenuated.

The decision statistic is given by [141]

$$E_{MRC} = \sum_{k=1}^{N} w_k E_k \tag{4.1.10}$$

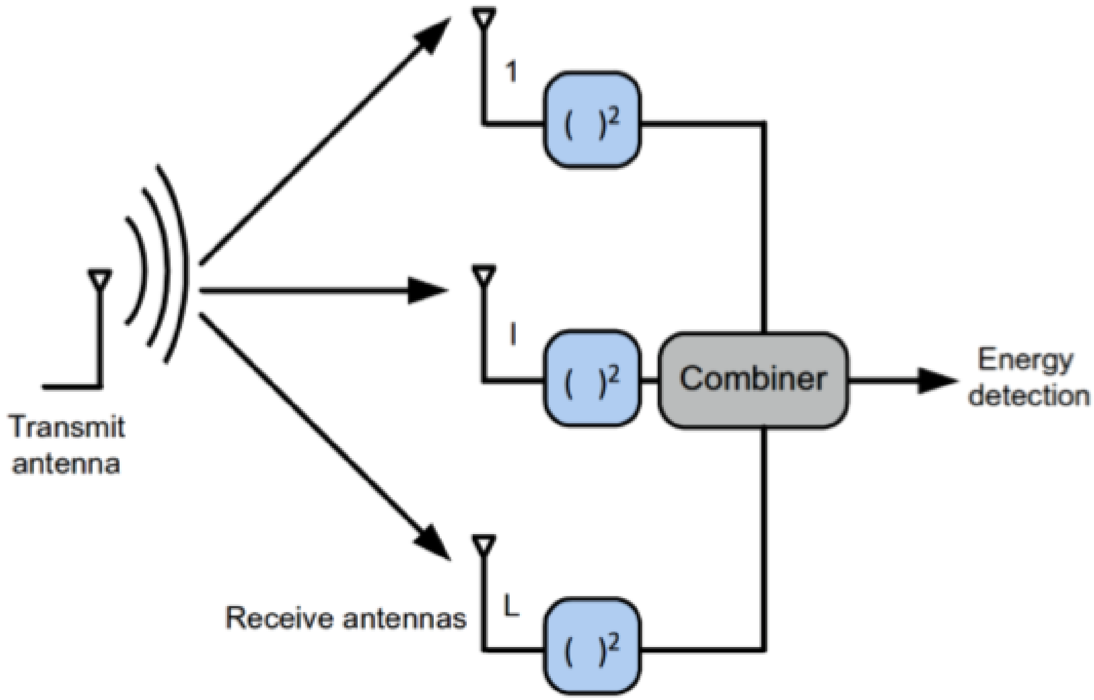


Figure 4.3: EGC based on Energy Detection

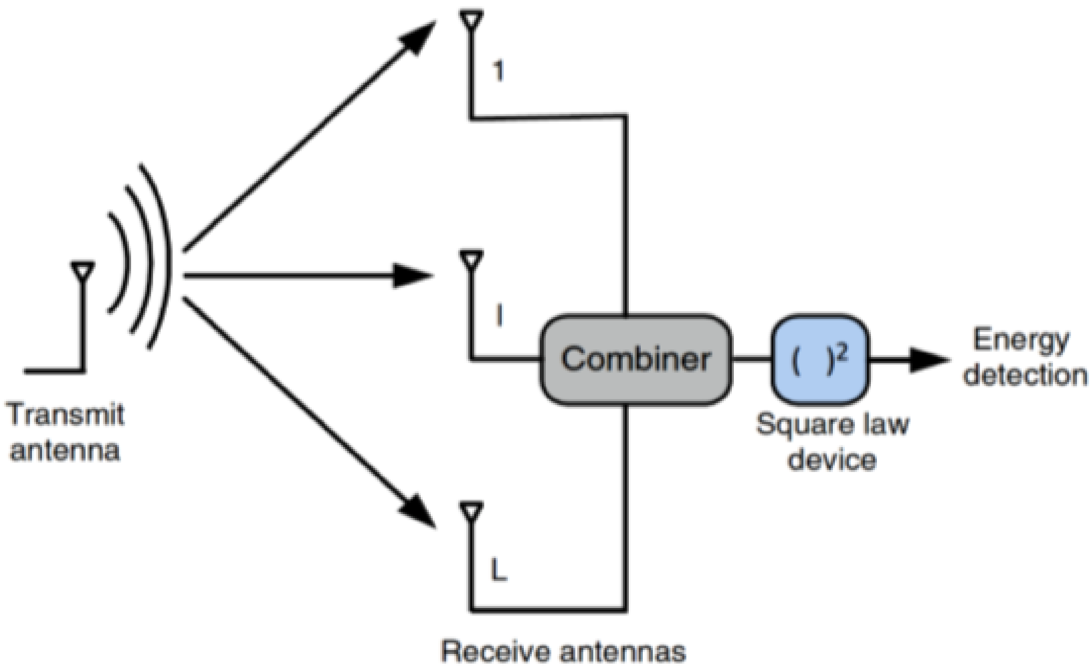


Figure 4.4: MRC based on Energy Detection

4.3 Energy Detection Technique for Spectrum Sensing

Energy detection technique, also called radiometry or periodogram [141] [142] [143], is the most common technique of spectrum sensing. This is because of its low computational and implementation complexities. In this method the receivers do not need any knowledge of the primary users' signal, hence it is the most generic compared to other techniques [144]. The signal detection is done by comparing the output of the energy detector with a threshold which is dependent on the noise.

Suppose the received signal has the following simple form:

$$y(n) = s(n) + w(n)$$

where, s(n) is the signal detected, n is the sample index, w(n) is the Additive White Gaussian Noise (AWGN) sample.

Note that s(n)=0 when there is no transmission by primary user. The decision metric for the energy detector can be written as

$$M = \sum_{n=0}^{N} |y(n)|^2 \tag{4.2.1}$$

N is the size of the observation vector.

By comparing the decision metric M with fixed threshold λ_E, the decision on the status of a band can be obtained.

This is corresponding to decide between following two hypotheses:

H_0: $y(n) = w(n)$,

H_1: $y(n) = s(n) + w(n)$

The performance of the detection algorithm can be summarized with two probabilities:

1. Probability of Detection P_D
2. Probability of False Alarm P_F

$$P_D = P_r (M > \lambda_E \mid H_1)$$

$$P_F = P_r (M > \lambda_E \mid H_0)$$

Figure 4.5 below shows Receiver Operating Characteristics (ROC) curves for energy detector under different SNR values [145].

ROC curves are used to assess the performance of a system. ROC curves are plots of the probability of detection (Pd) vs. the probability of false alarm (P_f) for a given signal-to-noise ratio (SNR).

The probability of detection (Pd) is the probability of saying that "1" is true given that event "1" occurred. The probability of false alarm (P_f) is the probability of saying that "1" is true given that the "0" event occurred. In spectrum sensing, the "1" event indicates that a primary user is present, and the "0" event indicates that a primary user is not present.

A detector's performance is measured by its ability to achieve a certain probability of detection and probability of false alarm for a given SNR. Examining a detector's ROC curves provides insight into its performance.

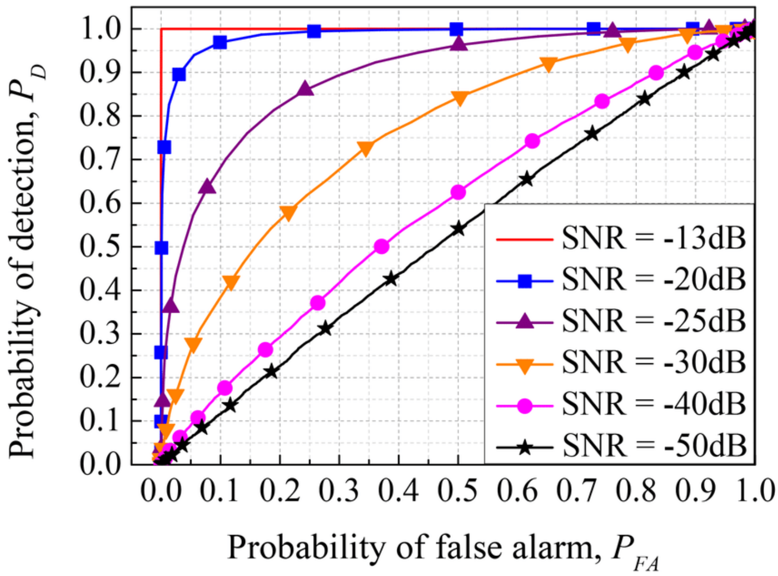


Figure 4.5 ROC curves for Energy Detector-based Spectrum Sensing under different SNR values

4.4 Improved Energy Detector (IED)

Improved energy detector functions better than classical energy detection-based scheme and also it preserves the same level of algorithm complexity. It also does not depend on a particular signal format to be detected [146].

Classical energy detection performance can be further improved if the misdetections caused by instantaneous signal energy drops could be avoided. This idea is the motivation behind the development of IED.

In this scheme, if the result of test statistic is less than a predefined threshold, an additional check is carried out before deciding the final channel state. This is because sometimes a busy channel is declared as idle due to instantaneous signal energy drop (because of particular radio propagation conditions and signal energy variation pattern) with a short sensing period.

In figure 4.6, two cases of interest are shown as event A and B at sensing event number 15 and sensing event number 35 respectively.

As per this additional verification step, if a particular sensing event reports an idle channel, the decision is not taken on this single check. An additional check of the average test statistic value of the last L sensing events is checked. If average value is greater than threshold, a signal is actually present in the sensed channel. As a result, a channel is declared as busy.

One more check is performed to avoid false alarms of event B. This check is based on the result of previous sensing event.

When $T_i(y_i) < \lambda$ and Ti^{avg} $(T_i) > \lambda$, one more condition of T_{i-1} $(y_{i-1}) > \lambda$ indicates that $T_i(y_i) < \lambda$ is because of instantaneous energy drop and so hypothesis H1 is selected. But in this case if T_{i-1} $(y_{i-1}) < \lambda$ then T_i $(y_i) < \lambda$ is due to the channel release. Now hypothesis H_0 is selected.

It is seen that the algorithm decisions could be based simply based on T_i (y_i) and $T_{i-1}(y_{i-1})$. However, the additional use of T_i^{avg} (T_i) avoids misdetections for highly variable signals where various consecutive sensing events may be affected by instantaneous energy drops, in which case $T_i(y_i) < \lambda$ and $T_{i-1}(y_{i-1}) < \lambda$ even though a primary signal is actually present in the channel. IED algorithm is shown in figure 4.7 [146] [147].

Simulation results of IED for GSM (900 MHz), DCS (1840 MHz), UHF_TV (725 MHz) and FM (93.5 MHz) are shown in figures below. All these results are also compared with classical energy detector. IED performs better than CED in all cases.

As seen from the results, for all four cases, the probability of detection is higher when IED is applied compared to CED. Also, Probability of false alarm is less with the IED compared to CED. IED gives better result because it checks two criterions of average values as well as instantaneous energy drop.

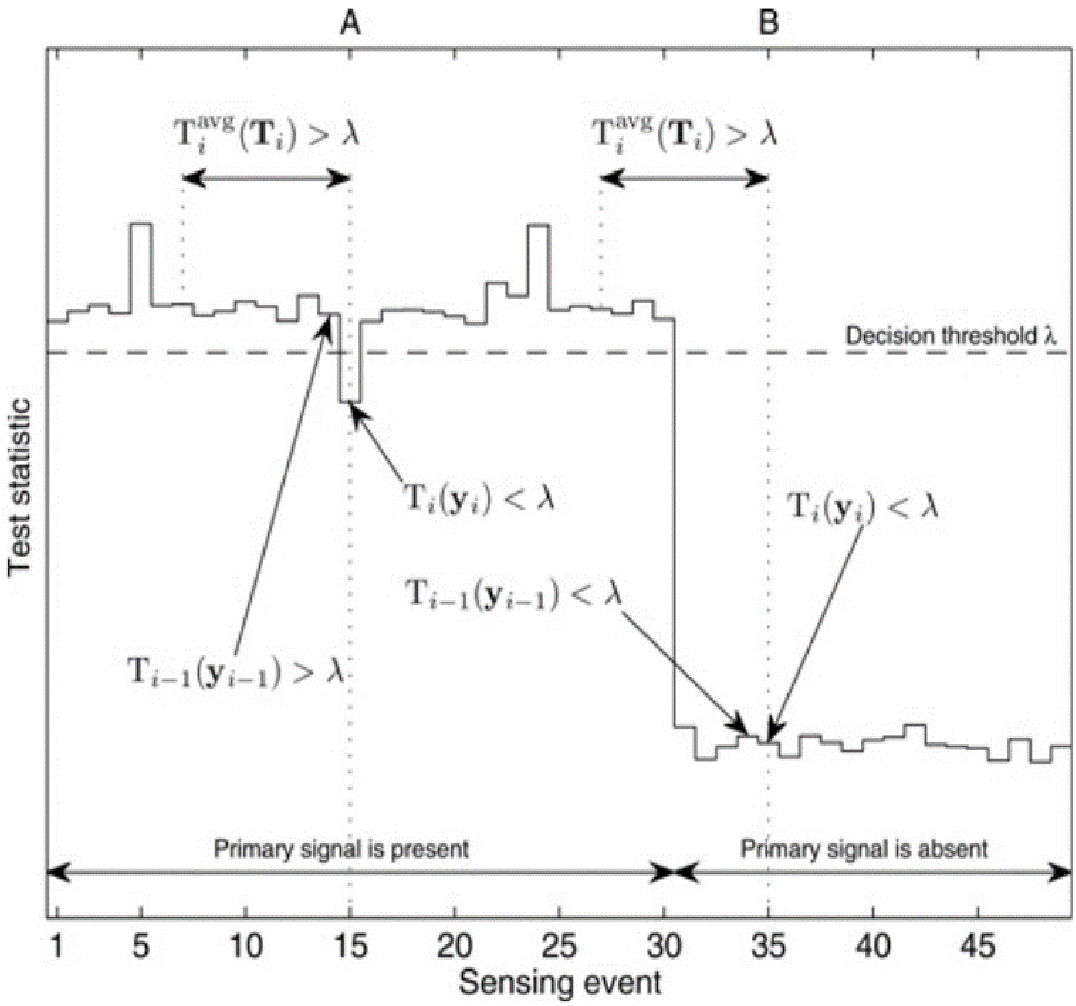


Figure 4.6 Improved Energy Detector

Algorithm for IED

Input: $\lambda \in R^{+}, N \in n, L \in n$

Output: $S_i \in \{H_0, H_1\}$

for each sensing event i do

  $T_i(y_i) \leftarrow$ Energy of N samples

  $T_i^{avg}(T_i) \leftarrow$ Mean of $\{T_{i-L+1}(y_{i-L+1}), T_{i-L+2}(y_{i-L+2}), \ldots\ldots T_{i-1}(y_{i-1}), T_i(y_i)\}$

  If $T_i(y_i) > \lambda$ then

    $S_i \leftarrow H_1$

  else

    if $T_i^{avg}(T_i) > \lambda$ then

      if $T_{i-1}(y_{i-1}) > \lambda$ then

        $S_i \leftarrow H_1$

      else

        $S_i \leftarrow H_0$

      end if

    else

      $S_i \leftarrow H_0$

    end if

  end if

end for

Figure 4.7 IED Algorithm

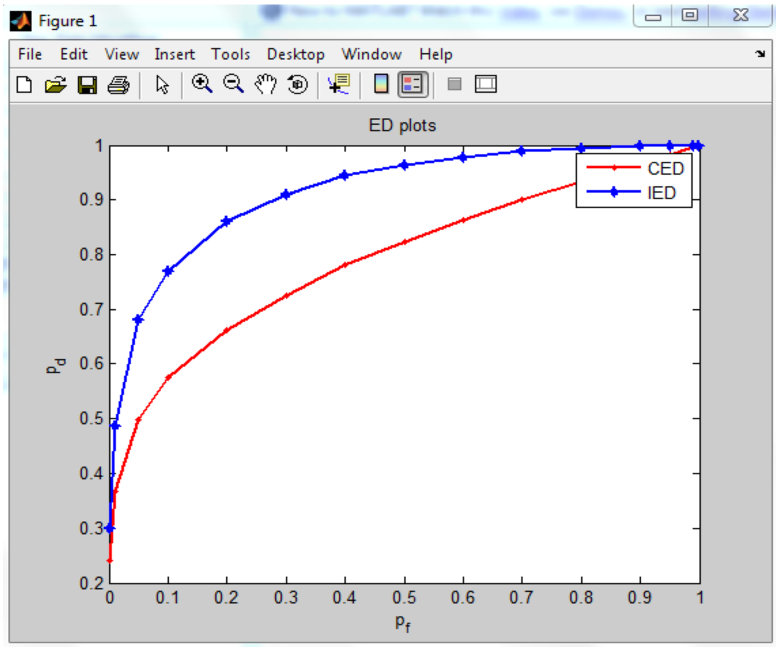


Figure 4.8 Simulation Result of IED for GSM (900 MHz)

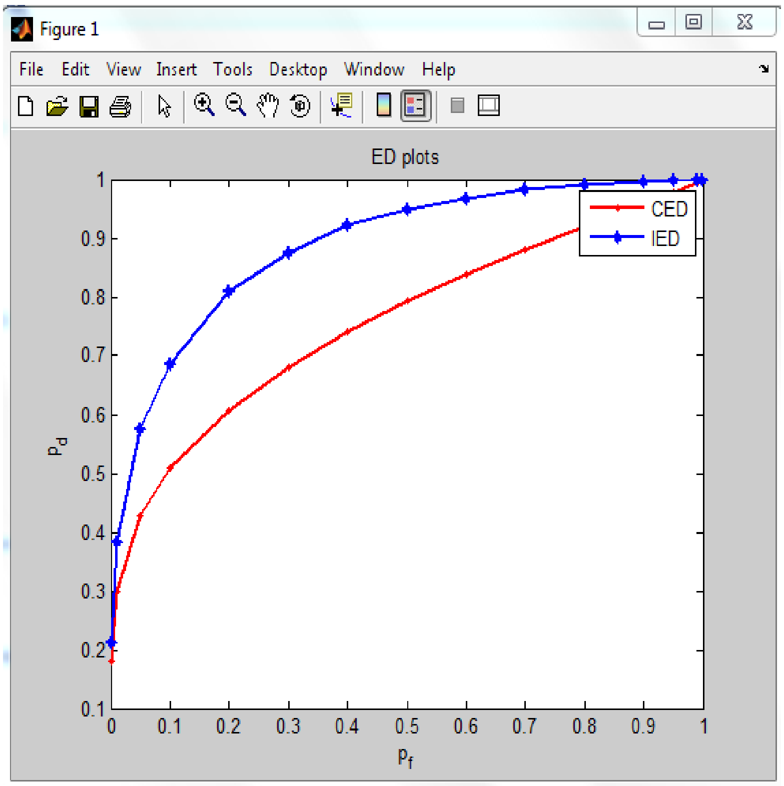


Figure 4.9 Simulation Result of IED for DCS (1840 MHz) Results

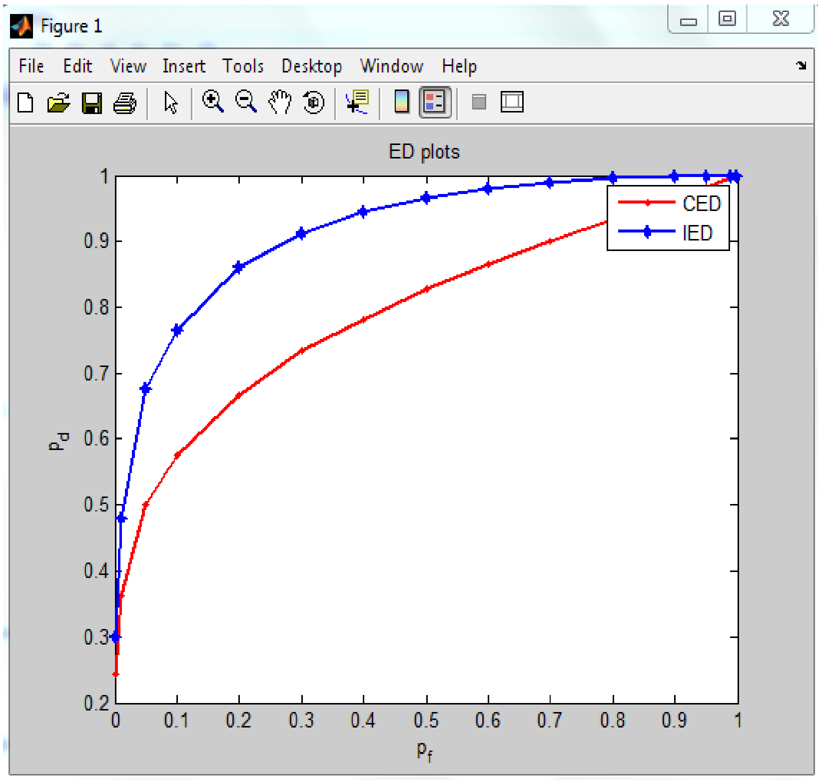


Figure 4.10 Simulation Result of IED for UHF_TV (725 MHz)

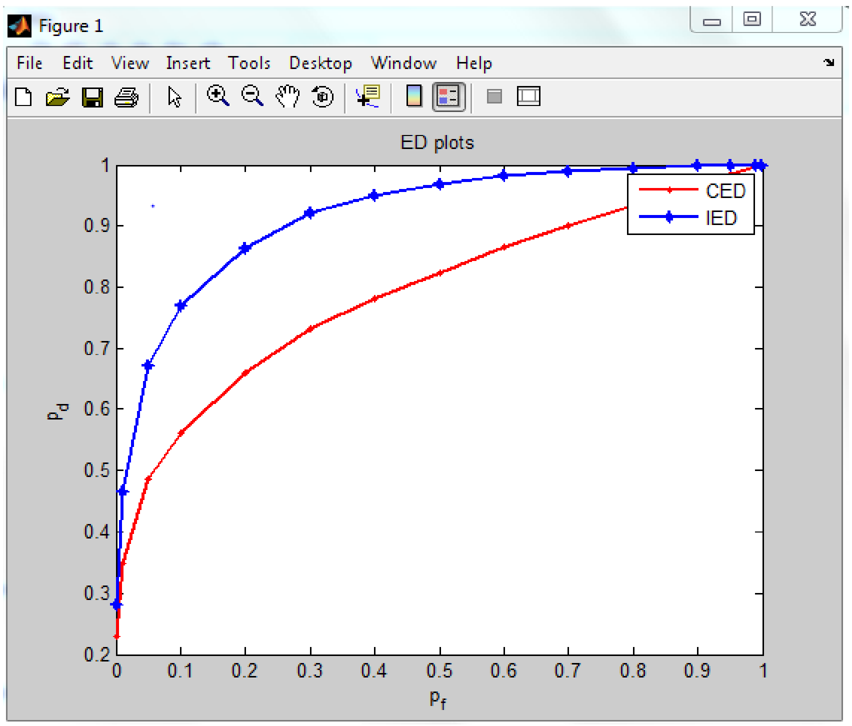


Figure 4.11 Simulation Result of IED for FM (93.5 MHz)

4.5 System Model

The system model for Jaya based softened hard Cooperative Spectrum Sensing method is shown in figure 4.12. In this, the spectrum is sensed locally by each CR. It sends 2-bit information "quantized observation" in the form of index L_n to the FC. The energy level for the local observation of CR user is indicated by index L_n. Based on the index of energy level L_n and weight vector w of corresponding energy level, the Fusion center (FC) makes global decision [148].

The division of entire sensing energy through three thresholds λ1, λ2 and λ3 depicts the basic difference between this framework and convention 1-bit hard fusion. In 1-bit HDF based cooperative spectrum sensing scheme, there is one threshold which splits the whole range of the observed energy into two regions, however in 2-bit scheme there are three thresholds which splits entire energy into four weighted level. As a result, all of the CR users above this threshold are assigned the same weight. This is regardless the possible significant differences in their observed energies.

The CR sends 2-bit information in the form of index L1, L2…., Ln to the Fusion Center (FC). The energy level for the local observation of CR user is indicated by index Ln. The fusion center makes a global decision according to index of energy level Ln and weight vector of corresponding energy level.

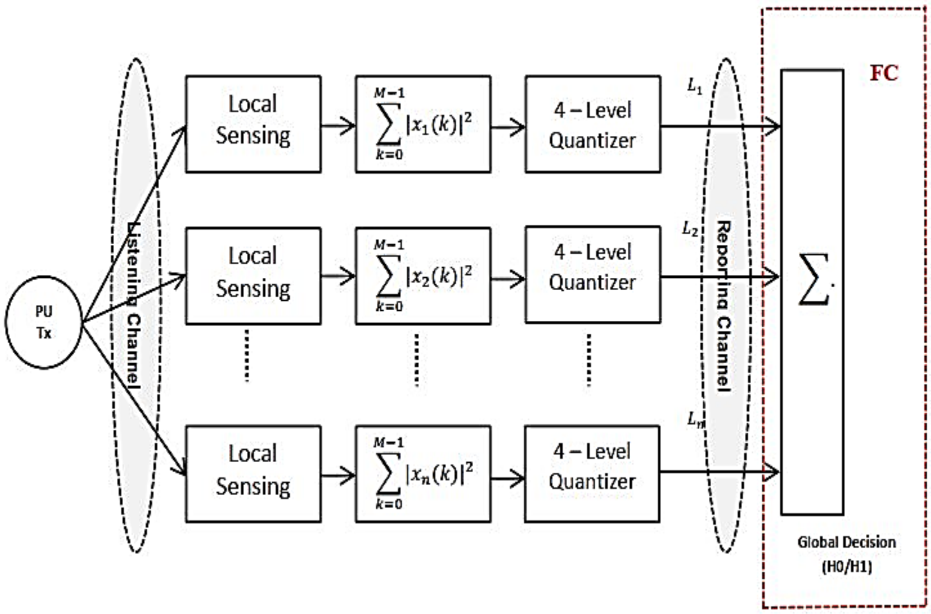


Figure 4.12 System Model for minimization of Sensing Error

4.6 JAYA Algorithm

In this research work, a simple yet powerful optimization algorithm is proposed [72], for solving the constrained and unconstrained optimization problems. The concept of the algorithm is that the solution obtained for given problem should move towards the best solution and should avoid the worst solution. This algorithm does not require any algorithm-specific control parameters, it requires only the common control parameters.

The Jaya Algorithm secures first rank for the best and mean solutions in the Friedman's rank test for all the twenty-four constrained benchmark problems. Apart from solving the constrained benchmark problems, Jaya algorithm is also investigated on 30 unconstrained benchmark problems taken from the literature and the performance of the algorithm is found better.

Dr. Rao proposed this another algorithm specific parameter less algorithm, keeping in view of the success of the Teaching Learning Based Optimization (TLBO) algorithm. This proposed algorithm has only one phase and it is comparatively simpler to apply, as compared to two phases (i.e. teacher phase and learner phase) of the TLBO Algorithm. The working of both the algorithm, the proposed algorithm and the TLBO algorithm are much different.

Suppose f(x) is the objective function to be minimized (or maximized). Assume that there are 'm' number of design variables (i.e. j=1, 2……, m) at any iteration 'i'. 'There are 'n' number of candidate solutions (i.e. Population size, k= 1, 2…., n). In the entire candidate solutions, let the best candidate obtains the best value of f(x) (i.e. $f(x)_{best}$) and the worst candidate obtains the worst value of f(x) (i.e. $f(x)_{worst}$). If $X_{j,k,i}$ is the value of the j^{th} variable for the k^{th} candidate during the i^{th} iteration, then this value is modified as per the following equation :

$$X'_{j,k,i} = X_{j,k,i} + r_{1,j,i}(X_{j,best,i} - |X_{j,k,i}|) - r_{2,j,i}(X_{j,\mathrm{worst},i} - |X_{j,k,i}|) \qquad (4.5.1)$$

Where, Xj,best,i is the value of the variable j for the best candidate and Xj,worst,i is the value of the variable j for the worst candidate. X'j,k,i is the updated value of Xj,k,i and r1,j,i and r2,j,i are the two random numbers for the jth variable during the ith iteration in the range [0, 1].

The tendency of the solution to move closer to the best solution is indicated by the term "$r_{1,j,i}$ (($X_{j,best,i}$- $|X_{j,k,i}|$)" and the tendency of the solution to avoid the worst solution is indicated by the term "-$r_{2,j,i}$ ($X_{j,worst,i}$- $|X_{j,k,i}|$)". X'j,k,i is accepted if it gives better function value. All the accepted function values at the end of iteration are maintained. These values become the input to the next iteration.

The flowchart of the Jaya algorithm is shown in Figure 4.13. The algorithm always tries to get closer to success (i.e. reaching the best solution) and tries to avoid failure (i.e. moving away from the worst solution). The algorithm strives to become victorious by reaching the best solution and hence it is named as Jaya (a Sanskrit word meaning victory).

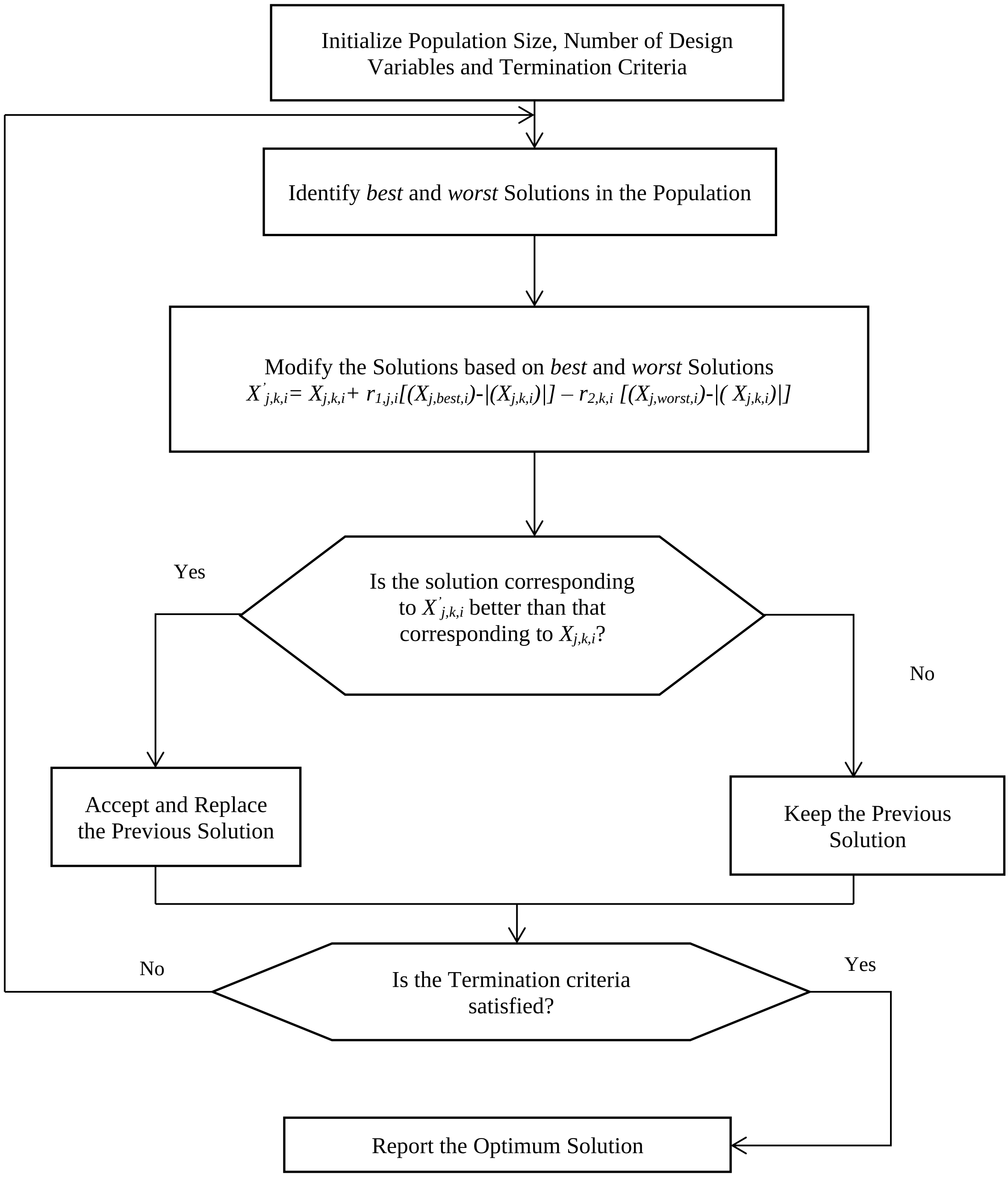


Figure 4.13 Flow Chart of JAYA Algorithm

To demonstrate the working of Jaya algorithm, an unconstrained benchmark function of Sphere is considered. The objective function is to find out the values of x_i that minimize the value of the Sphere function.

$$\min f(x_i) = \sum_{i=1}^{n} x_i^2 \tag{4.5.2}$$

subject to $100 \leq x_i \leq 100$

The known solution to this benchmark function is 0 for all xi values of 0. Now to demonstrate the Jaya algorithm, let us assume a population size of 5 (i.e. candidate solutions), two design variables x_1 and x_2 and two iterations as the termination criterion. The initial population is randomly generated within the ranges of the variables and the corresponding values of the objective function are shown in Table 4.1. As it is a minimization function, the lowest value of f(x) is considered as the best solution and the highest value of f(x) is considered as the worst solution.

Table 4.1 Initial Population

Candidate	x1	x2	f(x)	Status
1	-4	19	377	
2	15	64	4321	
3	71	-5	5066	Worst
4	-7	8	113	Best
5	-11	-17	410	

From Table 4.1, it can be seen that the best solution is corresponding the 4th candidate and the worst solution is corresponding to the 3rd candidate. Now assuming random numbers r1 = 0.58 and r2 = 0.81 for x1 and r1 = 0.92 and r2 = 0.49 for x2, the new values of the variables for x1 and x2 are calculated using equation 4.5.1 and are placed in Table 4.2. For example, for the 1st candidate, the new values of x1 and x2 during the first iteration are calculated as shown below.

Similarly, the updated values of x1 and x2 for the other candidates are calculated. Table 4.2 shows the updated values of x1 and x2 and the corresponding values of the objective function.

$X'_{1,1,1} = X_{1,1,1} + r_{1,1,1} (X_{1,4,1} - |X_{1,1,1}|) - r2,1,1 (X1,3,1 - |X1,1,1|)$

$= -4 + 0.58 (-7- | -4 |) -0.81 (71- | -4 |) = -64.65$

$X'2,1,1 = X2,1,1 + r1,2,1 (X2,4,1 - |X2,1,1|) - r2,2,1 (X2,3,1 - |X2,1,1|)$

$= 19 + 0.92 (8- | 19 |) - 0.49 (-5- | 19 |) = 20.64$

Table 4.2 New values of the Variables and the Objective Function during first iteration

Candidate	x1	x2	f(x)
1	-64.650	20.640	4605.630
2	-43.120	46.290	4002.100
3	25.760	2.660	670.6530
4	-66.960	14.370	4690.140
5	-70.040	-14.500	5115.850

Now, the values of f(x) of Tables 4.1 and 4.2 are compared and the best values of f(x) are considered and placed in Table 4.3. This completes the first iteration of the Jaya algorithm.

Table 4.3 Updated values of the variables and the objective function based on fitness comparison at the end of first iteration

Candidate	x1	x2	f(x)	Status
1	-4.0	19.0	377.0	
2	-43.120	46.290	4002.10	Worst
3	25.760	2.660	670.65	
4	-7.0	8.0	113.0	Best
5	-11.0	-17.0	410.0	

From Table 4.3 it can be seen that the best solution is corresponding the 4th candidate and the worst solution is corresponding to the 2nd candidate. Now, during the second iteration, assuming random numbers r1 = 0.27 and r2 = 0.23 for x1 and r1 = 0.38 and r2

= 0.51 for x2, the new values of the variables for x1 and x2 are calculated using Eq.4.5.1. Table 4.4 shows the new values of x1 and x2 and the corresponding values of the objective function during the second iteration.

Table 4.4 New values of the variables and the objective function during second iteration

Candidate	x1	x2	f(x)
1	3.8676	0.9021	15.7721
2	-36.817	31.7398	2362.92
3	32.7572	-17.562	1381.46
4	0.7476	-11.528	133.451
5	-3.4124	-35.358	1261.83

Now, the values of f(x) of Tables 4.3 and 4.4 are compared and the best values of f(x) are considered and placed in Table 4.5. This completes the second iteration of the Jaya algorithm.

Table 4.5 Updated values of the variables and the objective function based on fitness comparison at the end of second iteration

Candidate	x1	x2	f(x)	Status
1	3.8676	0.9021	15.7721	Best
2	-36.817	31.7398	2362.92	Worst
3	25.76	2.66	670.653	
4	-7	8	113	
5	-11	-17	410	

From Table 4.5 it can be seen that the best solution is corresponding the 1st candidate and the worst solution is corresponding to the 2nd candidate. It can also be observed that the value of the objective function is reduced from 113 to 15.7721 in just two iterations. If we increase the number of iterations then the known value of the objective function (i.e. 0) can be obtained within next few iterations. Also, it is to be noted that in the case of maximization function problems, the best value means the maximum value of the objective function and the calculations are to be proceeded accordingly. Thus, the proposed method can deal with both minimization and maximization problems.

JAYA algorithm is found in various field for optimization [81] [149].

4.7 Mathematical Statistics for Probability of Error

The probability of cooperative detection and probability of cooperative false alarm are evaluated as below:

$$P_d = \sum P\{\, cumulated\ local\ \ sensing\ \ result\ at\ FC = \ \vec{N}/H_1\}$$

$$P_d = \sum_{i=1}^{4}\sum_{j=1}^{4} P_r(N_1 = n_1, N_2 = n_2, N_3 = n_3, N_4 = n_4|H_1)$$

$$P_d = \sum f\left(\underset{w}{\rightarrow}\right)\binom{N}{n1}\binom{N-n1}{n2}\binom{N-n1-n2}{n3}\binom{N-n1-n2-n3}{n4} \dots\dots\dots\dots\dots\dots$$
$$-\cdots \dots..(1-P_{d1})^{n1}\,(P_{d1}-P_{d2})^{n2}\,(P_{d2}-P_{d3})^{n3}\,(P_{d4})^{n4}$$

Similarly, the probability of false alarm can be evaluated as below:

$$P_f = \sum P\{\, cumulated\ local\ \ sensing\ \ result\ at\ FC = \ \vec{N}/H_0\}$$

$$P_f = \sum_{i=1}^{4}\sum_{j=1}^{4} P_r(N_1 = n_1, N_2 = n_2, N_3 = n_3, N_4 = n_4|H_0)$$

$$P_f = \sum f(\vec{w})\binom{N}{n1}\binom{N-n1}{n2}\binom{N-n1-n2}{n3}\binom{N-n1-n2-n3}{n4} \dots\dots\dots\dots\dots\dots$$
$$-\cdots \dots..(1-P_{f1})^{n1}\,(P_{f1}-P_{f2})^{n2}\,(P_{f2}-P_{f3})^{n3}\,(P_{f4})^{n4}$$

The overall Probability of Error can be represented as

$$P_e = P_f + P_m$$

$$P_e = P_f(\vec{w}) + 1 - P_d(\vec{w})$$

Thus, probability of error depends on weight vector $\vec{w}$.

The most suitable optimality criteria are the Mini-Max criteria that minimize the probability of error. Proposed Jaya algorithm needs to optimize the weight vector $\vec{w}$ so the optimization problem is given by:

Optimization Problem for Jaya algorithm: Minimize P_e subject to $-5 \leq wi \leq 5$

4.8 Optimization Techniques used for best Spectrum Selection

4.8.1 Analytic Hierarchy Process (AHP)

Thomas Saaty [150] [151] developed AHP in the 1970s as a way of dealing with weapons tradeoffs, resource, asset allocation and decision making. AHP is a decision-making tool that can help describe the general decision operation by decomposing a complex problem into a multi-level hierarchical structure of objectives, criteria, sub-criteria, and alternatives. AHP can be used in making decisions that are complex, unstructured, and contain multiple attributes. AHP provides a method to connect that can quantify the subjective judgment of the decision maker in a way that can be measured. AHP is a method of breaking down a complex, unstructured situation into its component's parts, arranging these parts or judgments on the relative importance of each variable, and synthesizing the judgments to determine which variables have the highest priority and should be acted upon to influence the outcome of the situation [152].

Saaty allowed some measures of inconsistency (common with subjective human judgment) when applied to the logic of preferences. Inconsistencies arise when comparing three items, A, B, and C. For example, if item A is more preferred over item

B, and item B is more preferred over item C, then by the transitive property, Item A should be more preferred over item C. If not, then the comparisons are not consistent. AHP uses derived weights that show the importance of various criteria. AHP allow for individual attribute preferences or inconsistency measures.

AHP consists of four steps. One, define the problem and state the goal or objective. Two, define the criteria or factors that influence the goal. Structure these factors into levels and sublevels. Three, use paired comparisons of each factor with respect to each other that forms comparison matrix with calculated weights, ranked eigenvalues, and consistency measures [153]. Four, synthesize the ranks of alternatives until the final choice is made. The schematic representation of AHP is shown in Figure 4.14.

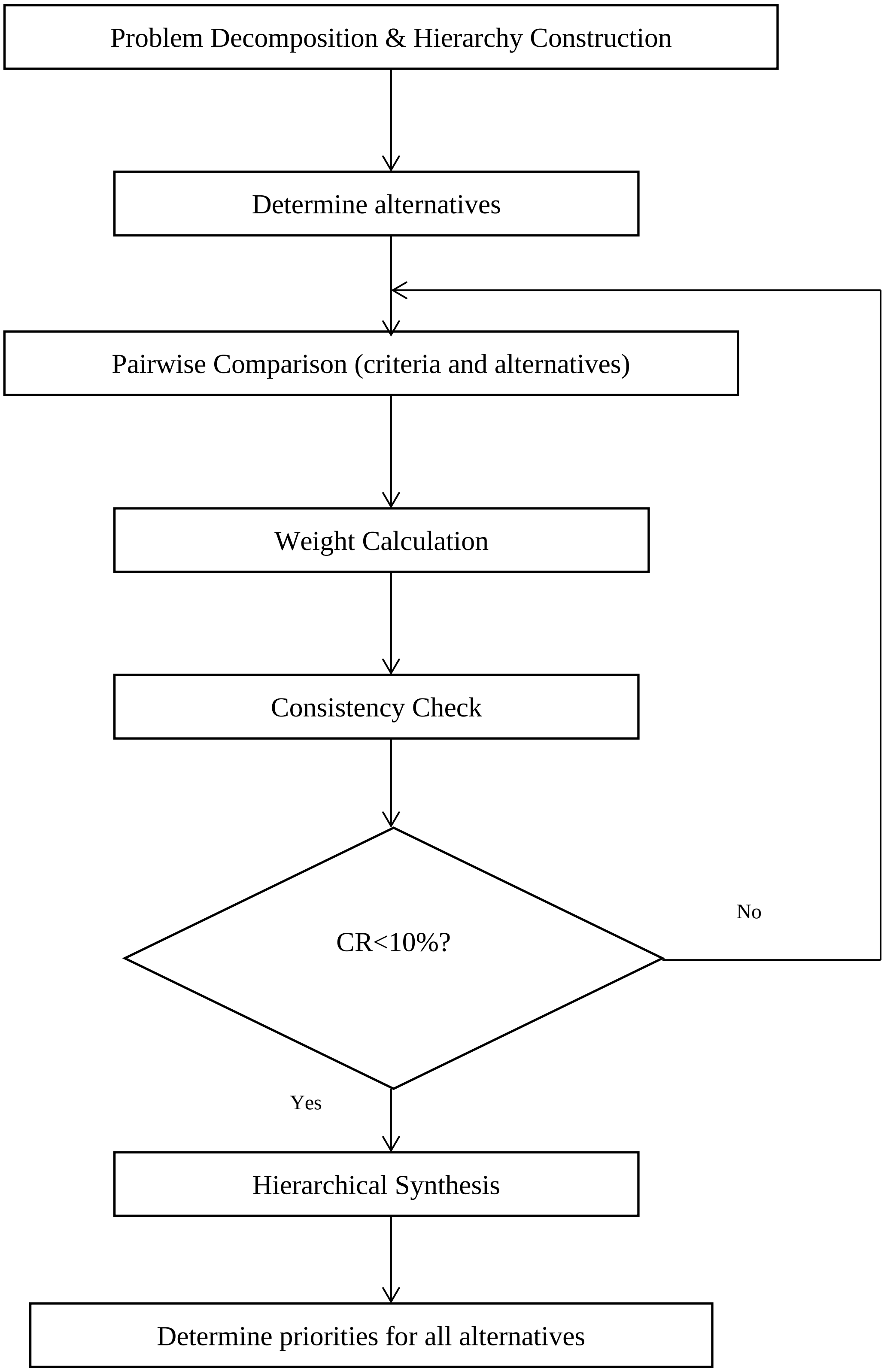


Figure 4.14 Schematic representation of the AHP method

4.8.2 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS is a multi-criteria method developed by Yoon and Hwang [154] to identify solutions from finite set of alternatives. Multi criteria decision making (MCDM) methods are the multi objective optimization techniques that has been used to evaluate the alternatives. The objectives with the highest relative closeness to the positive solution are suggested for optimal combination of input parameters. The basic principle is that the chosen alternative should have the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution. In recent years, TOPSIS has been successfully adopted in various fields of Communication [155].

The procedure of TOPSIS can be expressed in a series of following steps:

Step 1: Calculate the normalized decision matrix. The normalized value n_{ij} is calculated as:

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}^{2}}} \tag{4.6.1}$$

Step 2: Calculate the weighted normalized decision matrix. The weighted normalized value v_{ij} is calculated as:

$$v_{ij} = w_i * n_{ij},\ j = 1,....,m, i = 1,.....,n \tag{4.6.2}$$

Step 3: Determine the positive ideal and negative ideal solution

$$A+ = \left\{v_1^{+},.....v_n^{+}\right\} = \left\{(\max{}_j * vij \,/\, i \in I), (\min{}_j * vij \,/\, i \in J)\right\} \tag{4.6.3}$$

$$A^{-} = \left\{v_1^{-},.....v_n^{-}\right\} = \left\{(\max{}_j * vij \,/\, i \in I), (\min{}_j * vij \,/\, i \in J)\right\} \tag{4.6.4}$$

Where I is associated with benefit criteria and J is associated with cost criteria.

Step 4: Calculate the separation measure using the n-dimensional Euclidean distance. The separation of each alternative from the ideal solution is given as:

$$d_j^{+} = \sqrt{\left\{\sum_{i=1}^{n} (v_{ij} - v_i^{+})\right\}},\ j = 1,....m \tag{4.6.5}$$

$$d_j^- = \sqrt{\left\{\sum_{i=1}^{n}(v_{ij} - v_i^-)\right\}}, \; j = 1, \ldots .m \qquad (4.6.6)$$

Step 5: Calculate the relative closeness to the ideal solution. The relative closeness of the alternative Aj with respect to A+ is defined as:

$$R_j = d_j^- / (d_j^+ + d_j^-), \; j = 1, \ldots ..m \qquad (4.6.7)$$

Since $d_j^- \geq 0$ and $d_j^+ \geq 0$, then clearly Rj ∈ [0, 1].

CHAPTER-5

Results and Discussion

This chapter discusses Results of JAYA algorithm to optimize minimum probability of error and results are compared with TLBO algorithm. Also, the selection of best free spectrum is optimized using AHP and combined AHP and TOPSIS methods.

5.1 Minimization of Probability of Error

The performance of proposed JAYA algorithm is checked by the simulation. Comparison of Probability of Error (Pe) versus λ is shown in figure 5.1. It is compared with the conventional SDF technique EGC and convention HDF technique OR rule. It can be clearly observed that the JAYA algorithm generates the best weighting coefficients vector which gives minimized probability of error for Cooperative Spectrum Sensing in comparison to other schemes.

The convergence performance of JAYA algorithm is shown in figure 5.2 and also compared with the convergence of TLBO Based algorithm. JAYA algorithm performs better than TLBO and it is so fast for convergence that can guarantee real time requirements of cooperative spectrum sensing in Cognitive Radio. The value of Probability of Error 0.23 at threshold value of 8 in just 16 iterations is obtained by using Jaya Algorithm as shown in figure 5.1 and figure 5.2.

Simulation parameters for minimization of Probability of Error are shown in Table 5.1

Table 5.1 Simulation Parameters for minimization of Probability of Error

Parameter	Value
Time Bandwidth Product (TW)	5
Channel	AWGN
SNR	10 dB
Number of CR nodes	10
False Alarm Rate	0.01

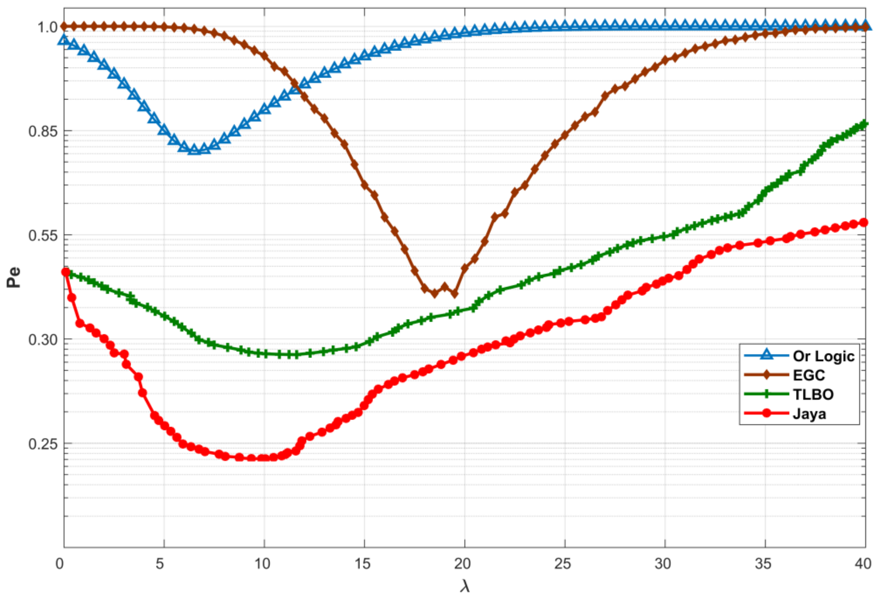


Figure 5.1 Probability of Error (P_e) versus λ

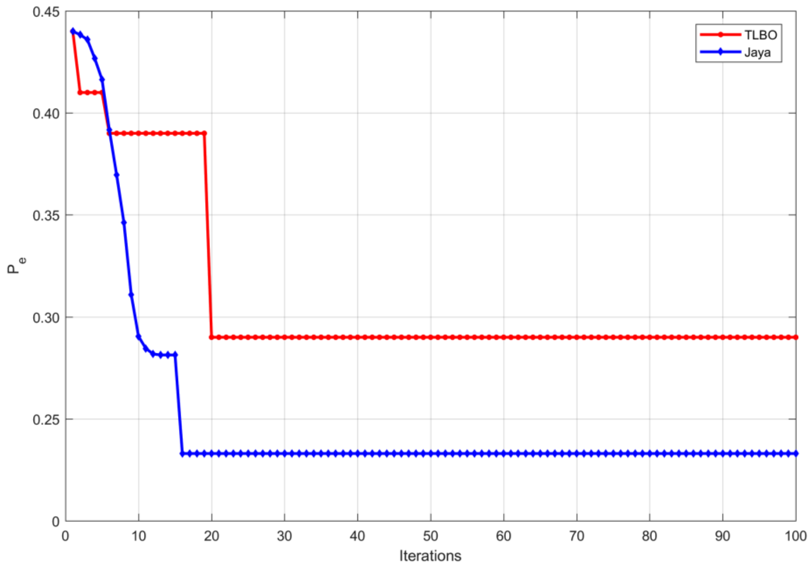


Figure 5.2 Probability of Error (P_e) versus Iterations

5.2 Selection of the best Spectrum

5.2.1 System Model using Analytic Hierarchy Process (AHP)

We consider a cognitive radio network consisting of a primary user and secondary user with a n number of transmission channels that can be used by a secondary user if not being used by the primary user. Each spectrum i is characterized by its Signal to Noise Ratio (SNR), the available bandwidth, the transmission power and the interference level. Those parameters are selected because of their dependence either to the channel capacity or quality of service. A channel can be selected to for transmission if it provides a better transmission throughout under higher transmission bandwidth, higher signal to noise ratio, low transmission power and low interference [156].

First step in the cognitive radio is spectrum sensing to find the spectrum holes. one state representing the activity times and the other as inactivity times, referred to as busy and idle states respectively. In the binarization process a spectrum hole is identified as “1” if the spectrum hole is available and can be utilized by the secondary user and as “0” if the spectrum is occupied by the Primary users or other secondary users.

A set of characteristics of an available spectrum will be evaluated by the spectrum management to ensure the selection of the best available spectrum. AHP is used to select the best available spectrum for secondary user [157].

5.2.2 Numerical Results

We have assumed a Cognitive Radio Network with a maximum of 8 spectrum holes that can be opportunistically detected at a specific period of time by the secondary user. The Spectrum Management Center (SMC) is able to communicate with secondary user and exchange the characteristics of the available spectrum for an efficient selection. The spectrum sensing gives the following spectrum binarization result: [0 1 1 0 0 1 1 0].

Table 5.1 below gives six spectrum characteristics for simulation purpose in terms of available Bandwidth (BW) in MHz, Signal to noise ratio (SNR) in dB, transmission power (Pw) in dBm and interference (INT) in dB.

Table 5.1 Spectrum Characteristics Matrix [77]

Spectrum	BW (MHz)	SNR (dB)	Pw (dBm)	INT (dB)
1	20	8	38	2.76
2	25	14	33	2.15
3	15	14	32	3.92
4	25	10	38	3.75
5	20	13	32	5.58
6	20	12	29	2.42
7	20	13	28	4.79
8	25	11	35	4.77

Table 5.2 Normalized Matrix for Spectrum Characteristics

Spectrum	BW (MHz)	SNR (dB)	Pw (dBm)	INT (dB)
1	0.8000	0.5714	0.7368	0.7790
2	1.0000	1.0000	0.8485	1.0000
3	0.6000	1.0000	0.8750	0.5485
4	1.0000	0.7143	0.7368	0.5733
5	0.8000	0.9286	0.8750	0.3853
6	0.8000	0.8571	0.9655	0.8884
7	0.8000	0.9286	1.0000	0.4489
8	1.0000	0.7857	0.8000	0.4507

Table 5.3 Comparison Matrix

	BW	SNR	Pw	INT
BW	1	2	3	4
SNR	1/2	1	3/2	2
Pw	1/3	2/3	1	4/3
INT	1/4	1/2	3/4	1

Calculated weights for above comparison matrix are 0.5361, 0.2681, 0.1787 and 0.1340 for BW, SNR, Pw and INT respectively.

5.2.3 Consistency test

Saaty [151] defined the consistency index (CI) as

$$CI = \lambda \max - M /(M - 1) \qquad (5.2.1)$$

Where, λmax is the maximum eigen value and M is the number of factors in the judgment matrix.

Accordingly, Saaty defined the consistency ratio (CR) as

$$CR = CI / RI \qquad (5.2.2)$$

For each size of matrix M, random matrices were generated and their mean CI value, called the random index (RI). RI represents the average consistency index over numerous random entries of same order reciprocal matrices. The consistency ratio CR is a measure of how a given matrix compares to a purely random matrix in terms of their consistency indices. A value of the consistency ratio CR ≤ 0.1 is considered acceptable.

With calculations on table 5.3 data and resulting weights CR value is 0 which is acceptable.

5.2.4 Priority and Result

With AHP method, priority values are 0.818156, 1.089836, 0.819609, 0.936111, 0.885817, 0.950279, 0.916672 and 0.950112 for 1 to 8 spectrums respectively. From these priority values and as shown in figure 5.3 below, ranking of spectrums for secondary users is 2-6-8-4-7-5-3-1.

From the above results, we can see that the secondary user can select spectrum 2 and 6 for his transmission with spectrum 2 having the most desirable transmission quality with a very good available bandwidth and signal to noise ratio.

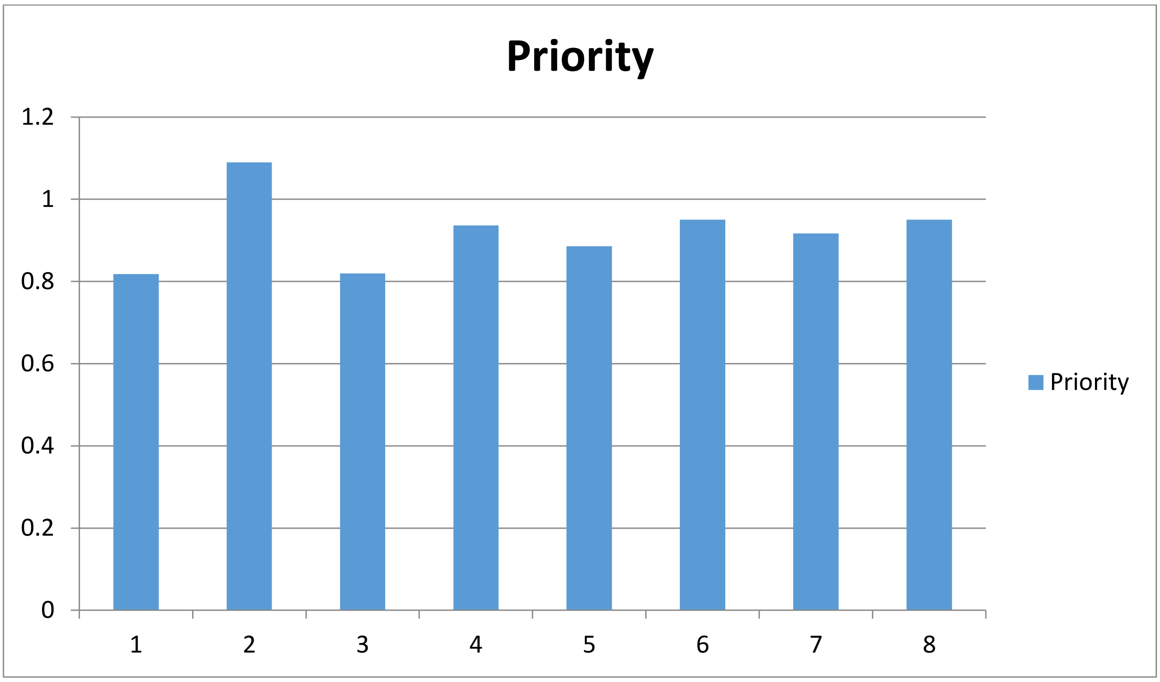


Figure 5.3 Spectrum Priority Result

5.2.5 System Model using combination of Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Analytic Hierarchy Process (AHP)

Here, combination of TOPSIS and AHP is used to select the best available spectrum for secondary user with all other parameters remains same as above method.

5.2.6 Numerical Results

We have assumed a Cognitive Radio Network with a maximum of 8 spectrum holes that can be opportunistically detected at a specific period of time by the secondary user. The Spectrum Management Center (SMC) is able to communicate with secondary user and exchange the characteristics of the available spectrum for an efficient selection. The spectrum sensing gives the following spectrum binarization result: [0 1 1 0 0 1 1 0].

Table 1 gives six spectrum characteristics for simulation purpose in terms of available Bandwidth (BW) in MHz, Signal to noise ratio (SNR) in dB, transmission power (Pw) in dBm and interference (INT) in dB. Calculated weights by AHP method are 0.5361, 0.2681, 0.1787 and 0.1340 for BW, SNR, Pw and INT respectively.

Table 5.4 Spectrum Characteristics Matrix [77]

Spectrum	BW (MHz)	SNR (dB)	Pw (dBm)	INT (dB)
1	20	8	38	2.76
2	25	14	33	2.15
3	15	14	32	3.92
4	25	10	38	3.75
5	20	13	32	5.58
6	20	12	29	2.42
7	20	13	28	4.79
8	25	11	35	4.77

Table 5.5 Normalized Matrix for Spectrum Characteristics

Spectrum	BW (MHz)	SNR (dB)	Pw (dBm)	INT (dB)
1	0.3288	0.2350	0.4034	0.2475
2	0.4110	0.4112	0.3503	0.1928
3	0.2466	0.4112	0.3397	0.3515
4	0.4110	0.2937	0.4034	0.3363
5	0.3288	0.3819	0.3397	0.5004
6	0.3288	0.3525	0.3078	0.2170
7	0.3288	0.3819	0.2972	0.4295
8	0.4110	0.3231	0.3715	0.4277

Table 5.6 Weighted Normalized Matrix

Spectrum	BW (MHz)	SNR (dB)	Pw (dBm)	INT (dB)
1	0.1763	0.0630	0.0721	0.0332
2	0.2203	0.1103	0.0626	0.0258
3	0.1322	0.1103	0.0607	0.0471
4	0.2203	0.0788	0.0721	0.0451
5	0.1763	0.1024	0.0607	0.0671
6	0.1763	0.0945	0.0550	0.0291
7	0.1763	0.1024	0.0531	0.0576
8	0.2203	0.0866	0.0664	0.0573

Table 5.7 Separation measure of positive, negative ideal solutions and relative closeness value

Sr.No.	S**	S*	Relative closeness (C*)	Rank
1	0.0678	0.0556	0.4508	7
2	0.0095	0.1086	0.9196	1
3	0.0910	0.0526	0.3662	8
4	0.0416	0.0922	0.6893	2
5	0.0613	0.0602	0.4953	6
6	0.0469	0.0684	0.5929	4
7	0.0549	0.0628	0.5337	5
8	0.0416	0.0919	0.6885	3

Where S** is Separation measure of positive ideal solution and S* is Separation measure of negative ideal solution.

5.2.7 Priority and Result

With TOPSIS method, relative closeness values are 0.4508, 0.9196, 0.3662, 0.6893, 0.4953, 0.5929, 0.5337 and 0.6885 for 1 to 8 spectrums respectively. From these priority values and as shown in Figure 5.4, ranking of spectrums for secondary users is 2-4-8-6-7-5-1-3. From the above results, we can see that the secondary user can select spectrum 2 and 4 for his transmission with spectrum 2 having the most desirable transmission quality with a very good available bandwidth and signal to noise ratio.

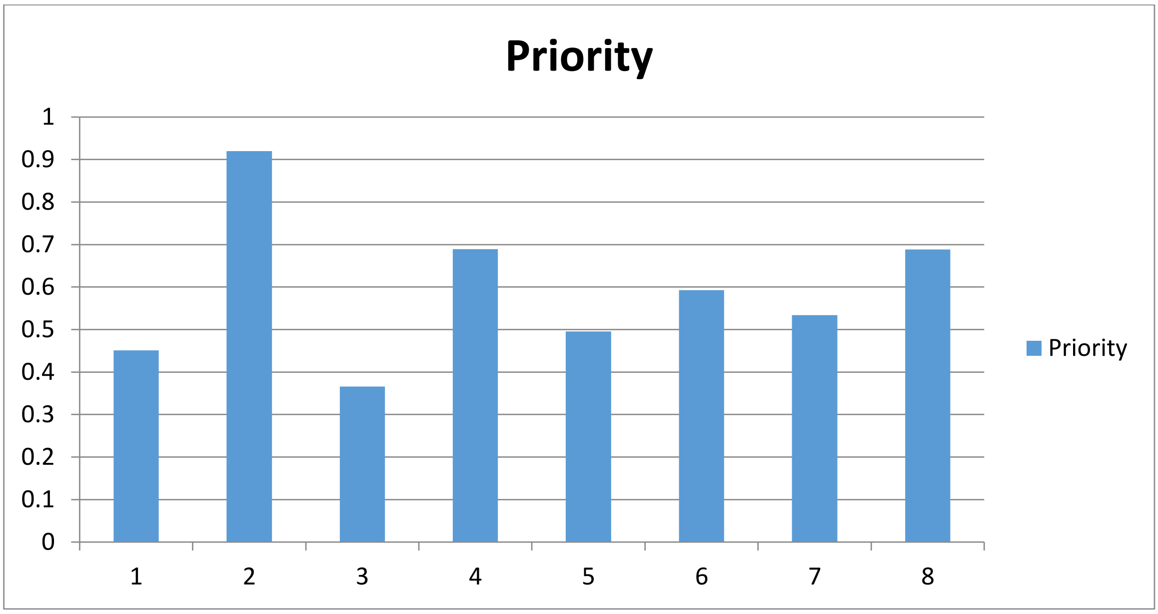


Figure 5.4 Spectrum Priority Result

The trade-offs map for spectrum sensing parameters [158] is shown in Figure 5.5. The below example explains the procedure to operate this map. See the number of secondary users, K. Then if K increases, there are two cases:

1. Throughput C increases because it is directly proportional to K. It is good for the system.
2. Sensing time τ decreases because it is inversely proportional to K. It is also good for the system.

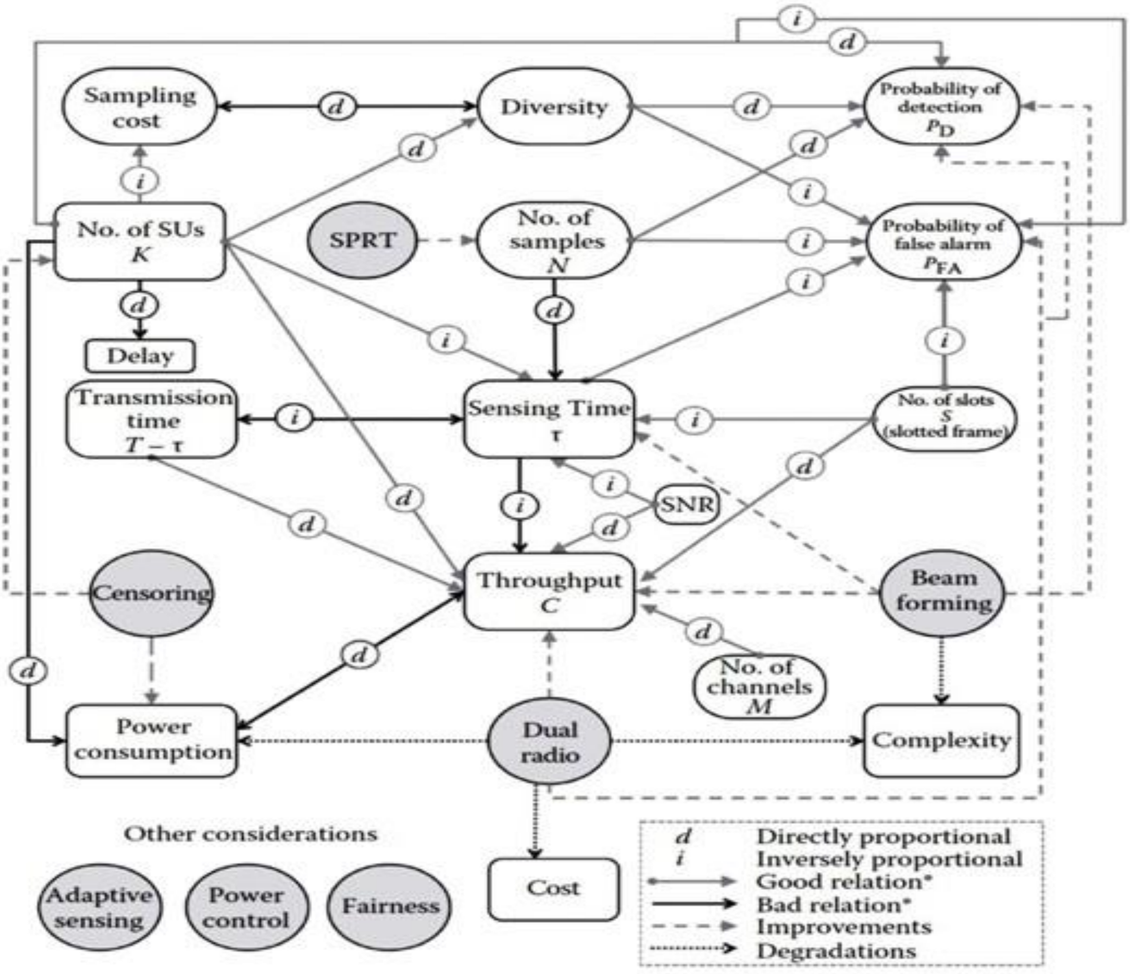


Figure 5.5 Trade off map for Spectrum sensing parameters

CHAPTER-6

Conclusion, Major Contribution and Future Scope

6.1 Conclusion

To meet high demand of spectrum in current era, Cognitive Radio plays an important role. Spectrum sensing is the main task of cognitive radio to find the free spectrum for Secondary Users. In this research work, energy detection technique is used to find the free spectrum. After finding free spectrum, this research work also works on selecting the best spectrum from available spectrums.

In this research work, Energy detection technique in cooperative manner is used for spectrum sensing and an advanced optimization technique Jaya algorithm is applied to get the minimum Probability of Error. Jaya algorithm is not found in literature for optimization of spectrum sensing. The concept of the Jaya algorithm is that the solution obtained for given problem moves towards the best solution and avoids the worst solution. This algorithm does not require any algorithm-specific control parameters, it requires only the common control parameters.

Comparison with other algorithm-specific parameter-less algorithm like Teaching Learning Based Optimization (TLBO) conclude that proposed Jaya algorithm utilized for optimizing CSS problem converges fast and finds the minimum probability of error in smaller number of iterations. In our research work, TLBO gives 0.29 Probability of Error at threshold value of 10 in 20 iterations and use of Jaya algorithm gives the value of Probability of Error 0.23 at threshold value of 8 in just 16 iterations. Thus, Jaya algorithm obtain 20% reduction in Probability of Error. Also, from the simulation results it is concluded that the proposed algorithm converges in a smaller number of iterations compared to TLBO. The performance of proposed Jaya algorithm is also compared with conventional Hard Decision Fusion and conventional Soft Decision Fusion techniques.

In addition to this, the best spectrum for secondary users from various available spectrums is selected using Analytic Hierarchy Process (AHP). AHP is a method of breaking down a complex, unstructured situation into its component's parts, arranging these parts or judgments on the relative importance of each variable, and synthesizing the judgments to determine which variables have the highest priority and should be acted upon to influence the outcome of the situation. Also, the best spectrum for secondary users from various available spectrums is selected using combination of AHP and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods in this research work.

6.2 Major Contributions

In this thesis, energy detection technique is used for spectrum sensing in cooperative manner. The use of Jaya algorithm as an optimization method is proposed to evaluate optimal weighting coefficient vector of sensing information. Also, the best spectrum is selected using Analytic Hierarchy Process (AHP) as well as combined AHP and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) optimization techniques.

The following summary shows the main contributions of this thesis:

1. Energy detection spectrum sensing is used to find free spectrum.
2. Jaya based cooperative spectrum sensing frame work is proposed. This optimize thresholds and the weighting coefficients vector of energy level of sensing information so that the total probability of error is minimized.
3. The performance of Jaya based cooperative spectrum sensing is compared with other conventional soft decision fusion schemes like Equal Gain Combining (EGC) as well as hard decision fusion like OR rule.
4. The performance of Jaya algorithm is compared with other advanced optimization technique like Teaching Learning Based Optimization (TLBO) for validation.
5. The selection of the best spectrum is carried out using Analytic Hierarchy Process (AHP) as well as combined AHP and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) optimization techniques.

6.3 Future Scope

There are some recommendations and potential research directions that extend this work as the scope of future work. The summaries for future scope of this work are following:

- Proposed JAYA based cooperative spectrum sensing framework can be extended with multiple cognitive networks.
- Other optimization algorithms can be applied which can give better results in smaller number of iterations.
- JAYA algorithm can be extended to optimize other parameters in cooperative spectrum sensing like Probability of Detection (P_d), Sensing time, Number of cooperative users etc.
- Performance of proposed method can be assessed with user mobility.

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List of Publication

1. A. A. Vithalani, Dr. C. H. Vithalani,” Application of combined TOPSIS and AHP method for Spectrum Selection in Cognitive Radio by Channel Characteristic Evaluation” International Journal of Electronics & Communication Engineering (IJECE)" ISSN 0974-2166, Volume 10, Number 2,2017, pp. 71-79.
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3. A. A. Vithalani, Dr. C. H. Vithalani, “A Survey on Optimization Techniques for Spectrum Sensing in Cognitive Radio” International Journal of Research in Electronics and Computer Engineering (IJRECE) ISSN: 2348-2281, Vol. 7, Issue 1 (January-March 2019), pp. 16-19. (UGC Approved Journal)
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