COOPERATIVE SPECTRUM SENSING IN COGNITIVE RADIO NETWORK

Ph.D. Thesis

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DECLARATION

I, **Girraj Sharma**, declare that this thesis titled, "**Cooperative Spectrum Sensing in Cognitive Radio Network**" and the work presented in it are my own. I confirm that:

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This is to certify that the thesis entitled **"Cooperative Spectrum Sensing in Cognitive Radio Network"** being submitted by **Mr. Girraj Sharma (2014REC9529)** is a bona fide research work carried out under my supervision and guidance in fulfillment of the requirement for the award of the degree of **Doctor of Philosophy** in the Department of Electronics and Communication Engineering, Malaviya National Institute of Technology, Jaipur, India. The matter embodied in this thesis is original and has not been submitted to any other University or Institute for the award of any other degree.

Place: Jaipur
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ABSTRACT

In the last decade there is a vast development in the wireless communication and new wireless devices so the demand of the radio spectrum is increasing, there is a need of efficient spectrum utilization because due to fixed assignment policy a huge portion of licensed spectrum is underutilized. To exploit the radio spectrum in a more intelligent and flexible way, regulatory bodies are reviewing their policies by adopting innovative communication technology. Cognitive Radio (CR) is a revolutionary technology, which enables access to, underutilized spectrum efficiently and dynamically without causing interference to the licensed users. Definition of CR as adopted by FCC: "Cognitive radio: A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets."

Each spectrum is assigned with certain bandwidth to only one or more dedicated users. Only the licensed users (primary users) have the right to use the assigned radio spectrum and no other users can use it. Due to this, a large portion of the licensed spectrum remains underutilized. To use the radio spectrum more efficiently, dynamic spectrum access techniques are adopted where users who have no license, known as secondary user (SU), are allowed to use the licensed spectrum temporarily.

The SUs need to detect the presence of vacate spectrum in the neighboring network. These vacate spectrum are known as spectrum holes (SH) or white spaces it should also be able to quit the frequency band when primary user (PU) starts communicating. This process is called spectrum sensing. Spectrum sensing is the first step to implement CR network. A single user sensing also known as non-cooperative spectrum sensing is the type of spectrum sensing in which CR acts on its own. There are some issues in non-cooperative spectrum sensing like noise uncertainty, fading and shadowing. Cooperative spectrum sensing (CSS) gives solution of these problems. In CSS, several SUs combine their findings to arrive at more reliable decision. CSS can mitigate the effects of hidden terminal and shadowing but in CSS energy resources become precious when the secondary users (SU) are battery operated. So it becomes important to use their energies efficiently. The Energy Efficiency (EE) is defined as the rate of data transmission per unit energy. EE is a comprehensive metric which represents the overall

performance of the CR because it jointly takes account of achievable throughput, detection accuracy, and overall energy consumption.

In this dissertation, detection and EE performance of CSS is investigated and a cluster based CSS scheme with different fusion rule is proposed. In the first part detection accuracy of energy detector, based cluster based CSS (CBCSS) is discussed over different fading channels and performance of CBCSS is improved by using different diversity combining techniques. In the second part EE performance of non-cluster and cluster-based CSS is discussed.

The effect of various fusion rules of CBCSS on EE is investigated. Joint fusion rule, sensing time and joint sensing duration and transmission power that maximizes the EE has been determined. A framework which jointly optimizes the fusion rule sensing time, transmission power and fusion rule, sensing time that maximizes the EE is proposed. To calculate the optimal design parameters iterative algorithms are proposed.

Results of the investigation show that for false alarm probability = 0.1, detection probability = 0.8 for cluster based OR-OR fusion and it is equals to 0.55 for OR fusion without clustering. Further, it is found that maximum Energy EE = 3.15 Mbits/Hz/Joule when sensing time and fusion rule threshold jointly optimized without clustering of secondary users. For this joint optimization optimum sensing duration = 0.841ms and fusion rule threshold = 4 at SNR = -18dB.

For cluster based CSS, AND-OR fusion outperforms the other fusion rules to maximize the EE. The maximum EE is 3.69 Mbits/Hz/joule at sensing time 1.5ms when number of clusters are 4 and number of users in the cluster are 3. For the same cluster based CSS, maximum EE = 3.735 Mbits/Hz/Joule when sensing time and transmission power are jointly optimized. The optimum sensing duration is 2.3 ms and transmission power $1.11W$ at primary SNR = -20dB.

LIST OF PUBLICATIONS

International Journals:-

1. Sharma, Girraj, and Ritu Sharma. “Joint Optimization of Fusion Rule Threshold and Transmission Power for Energy Efficient CSS in Cognitive Radio Networks." IEEE Transactions on Cognitive Communications and Networking (Under review)
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3. Girraj Sharma, Ritu Sharma, “Comparative analysis of hard fusion techniques for Energy Efficient CSS in Cognitive Radio”, National Conference on Advanced Communication Technology and Networks (ACTN-2017) MNIT, Jaipur.
4. Girraj Sharma, Ritu Sharma, “Cooperative spectrum sensing with SLS and transmit diversity in cognitive radio networks”. International conference on recent trends in engineering and material science (ICEMS-2016) Jaipur National university, Jaipur, India .March 17-19,2016.
5. Girraj Sharma, Ritu Sharma, “A Review on Recent Advances in Spectrum Sensing, Energy Efficiency and Security Threats in Cognitive Radio Network”. International Conference on Microwave, Optical and Communication Engineering (ICMOCE-2015) School of Electrical Sciences, IIT Bhubaneswar, Odisha, India, 18-20 December 2015. DOI: 10.1109/ICMOCE.2015.7489704

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LIST OF ABBREVIATIONS

AWGN	Additive white gaussian noise
BPSK	Binary phase shift keying
BS	Base station
CBSS	Cluster-based spectrum sensing
CCSS	Centralized cooperative spectrum sensing
CH	Cluster head
CR	Cognitive radio
CROC	Complementary receiver operating characteristic
CRN	Cognitive radio network
CSS	Cooperative spectrum sensing
DSA	Dynamic Spectrum Access
ED	Energy Detector
EGC	Equal gain combining
FC	Fusion center
FCC	Federal Communications Commission
i.i.d	Identical independent distributed
MAC	Medium Access Control Layer
MRC	Maximum ratio combining
OSI	Open Systems Interconnection
PHY	Physical Layer
PU	Primary user
QoS	Quality of Service
RF	Radio Frequency
ROC	Receiver operating characteristic
SC	Selection combining
SA	Spectrum Analysis
SD	Spectrum Decision
SH	Spectrum Hole

SS	Spectrum Sensing
SSh	Spectrum Sharing
SLC	Square law combining
SLS	Square law selection
SNR	Signal to noise ratio

LIST OF SYMBOLS

N	Number of secondary users
τ_s	Sensing time
τ_r	Reporting time
τ_d	Data transmission time
τ	Normalized sensing time $= \frac{\tau_s}{T}$
T	Total frame time
a_0	Mean values of exponential distribution of PU idle state
a_1	Mean values of exponential distribution of PU busy state
$f_0(t)$	Probability density functions of the idle PU states
$f_1(t)$	Probability density functions of the busy PU states
P_0	Probability of PU being idle
P_1	Probability of PU being busy
${P_f}^j$	False alarm probability at j^{th} CR
${P_d}^j$	Detection probability at j^{th} CR user
${\sigma_n}^2$	Noise power spectral density received at CR users
ε_j	Threshold of j^{th} CR user
P_e	Bit error rate between SU and FC
Q_f	Global probability of false alarm
Q_d	Global probability of detection
Q_m	Global probability of miss
L	Number of clusters
M	Number of SU users in a cluster
$\mathbb{E}$	Total energy consumption
$\mathbb{R}$	Average throughput
θ_s	Sensing power of each SU
θ_t	Transmission power of each SU

C	Transmitted data volume
f_s	Sampling frequency
β	Channel bandwidth
Γ	Noise power measured over channel bandwidth
ξ	Energy efficiency
δ	Target probability of detection
a_i	Maximum limit of interference level allowed to the PU
$\bar{P}_d$	Target detection probability of individual CR
θ_{max} , θ_{min}	Maximum and minimum value of transmission power
τ_0	Optimum value of normalized sensing time
$\theta_{t\,0}$	Optimum value of transmission power
q	Rician fading parameter
m	Nakagami fading parameter
k	Fading threshold
u	Time bandwidth product
V	Number of diversity branches
γ	SNR of secondary transmission
$\bar{\gamma}$	Average SNR
γ_1	SNR of primary transmissions

CHAPTER 1: INTRODUCTION

The wireless communication services has rapidly grown over the last two decades therefore the demand for electromagnetic radio frequency spectrum has increased. The radio frequency spectrum is a scarce resource. In a large geographical region, this spectrum is assigned to license holders. Due to this static frequency allocation a large portion of the spectrum, remain unused for a significant period of the time [1].

Since the radio spectrum is underutilized, the European Commission (EC) and Federal Communications Commission's (FCC) Radio Spectrum Policy Group, proposed a secondary transmission method and simultaneous usage of this frequency spectrum, where this secondary system does not interfere with the normal operation of the license holders. In the licensed bands entities such as radio stations or mobile operators are granted exclusive access but the new regulations by FCC allow the evolution of a new paradigm in which devices will have the ability to adapt to their spectral environment and able to make use of the available spectrum in an opportunistic manner. This paradigm shift paves the way for the development of the Cognitive Radio (CR).

The name CR was first put forward by J. Mitola III in [2] , as the evolution of the Software Defined Radio (SDR). Mitola presented CR as an intelligent agent which can track radio resources and related computer-to-computer communication. Later the focus of research in CR was directed mainly towards the opportunistic use of the radio resources, a technique also known as Dynamic Spectrum Access (DSA).

The concept of CR was further defined in [3, 4], giving emphasis to DSA. which led to a new CR definition: *an intelligent wireless communication system, aware of its surrounding environment (i.e., outside world), that uses the methodology of understanding-by-building to learn from the environment and to adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind: highly reliable communications whenever and wherever needed and efficient use of the radio spectrum.*

Currently there are several ongoing CR standardization efforts like IEEE 802.22 [5], IEEE 1900 [6] and the IEEE 802.11af.

1.1 The Fundamentals of Cognitive Radio

The key enabling technologies of CR are the functions that provide the capability to share the spectrum in an opportunistic manner. In [7] a summarized definition of CR is presented: A CR is a radio that can change its transmitter parameters based on interaction with the environment in which it operates. Since most of the spectrum is already assigned, the challenge is to share the spectrum with coexisting networks without interfering with their transmission. For this the CR enables the usage of temporarily unused spectrum, which is referred in the literature as Spectrum Hole (SH) or white space, which is shown in Figure 1.1. In [3], the definition of SH has been given: A SH is a band of frequencies allocated to a PU, but, at a specific time and particular geographic location, the band is not being used by that user. If this SH where the CR is operating starts also to be used by another SU, then the CR moves to another SH or stays in the same, changing its transmission power level or modulation scheme to reduce interference.

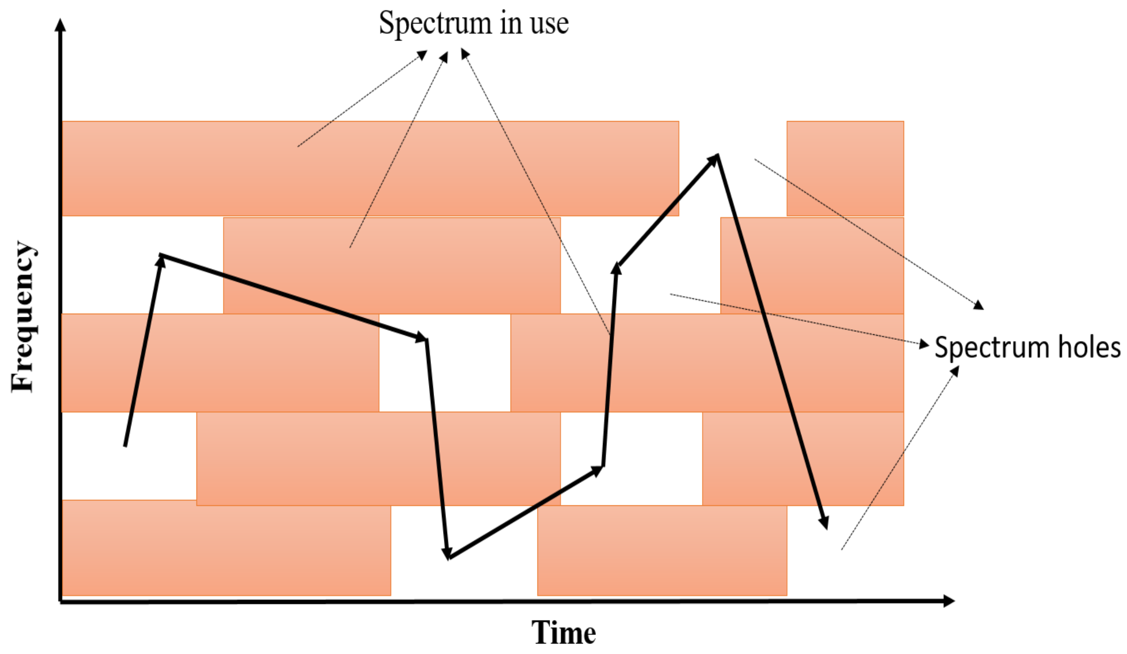

Figure 1.1 Spectrum hole concept [3]

The key functions of CR is:

- Determine the empty spectrums available;
- Select the best available channel;
- Coordinate access to this channel with other users;
- Evacuate it when the licensed user reappears.

To implement the CR model a network needs to employ adaptive network protocols. Such an example is given in [7, 8], where it is proposed a cross layer variation approach of the Open Systems Interconnection (OSI) network model to allows the implementation of the CR model. In this model, the spectrum sensing and spectrum sharing functions cooperate with each other to improve the network efficiency. In the spectrum decision and spectrum mobility function, application, transport, routing, medium access and physical layer functionalities are carried out in a cooperative way, so as to allow adapting to the dynamic nature of the underlying spectrum.

1.2 Functions of Cognitive Radio

The CR main goal is to enable networks to use the appropriate available spectrum band according to the network users Quality of Service (QoS) requirements. To accomplish this, new spectrum management functions are required, taking into consideration the dynamic spectrum characteristics. These functions are the Spectrum Sensing (SS), Spectrum Analysis (SA) and Spectrum Decision (SD), and their interrelation as depicted in Figure 1.2 [3, 9]. It is expected that the SS function will find SH spread over a wide frequency range including both unlicensed and licensed bands. Therefore, these will potentially show different characteristics accordingly not only to the time varying radio environment but also to the spectrum band information such as the operating frequency and the bandwidth. Due to the dynamic nature of the underlying spectrum, the communication protocols need to adapt to the wireless channel parameters.

In order to decide the appropriate spectrum band, the information regarding the QoS requirement, transport, routing, scheduling, and sensing is required. Therefore, the use of a cross layer approach will use the interdependency among functionalities of the communication stack, and their close coupling with the physical layer to accomplish the SA and SD function. So, while SS is primarily a Physical Layer (PHY) and MAC issue, SA and SD are closely related to the upper layers.

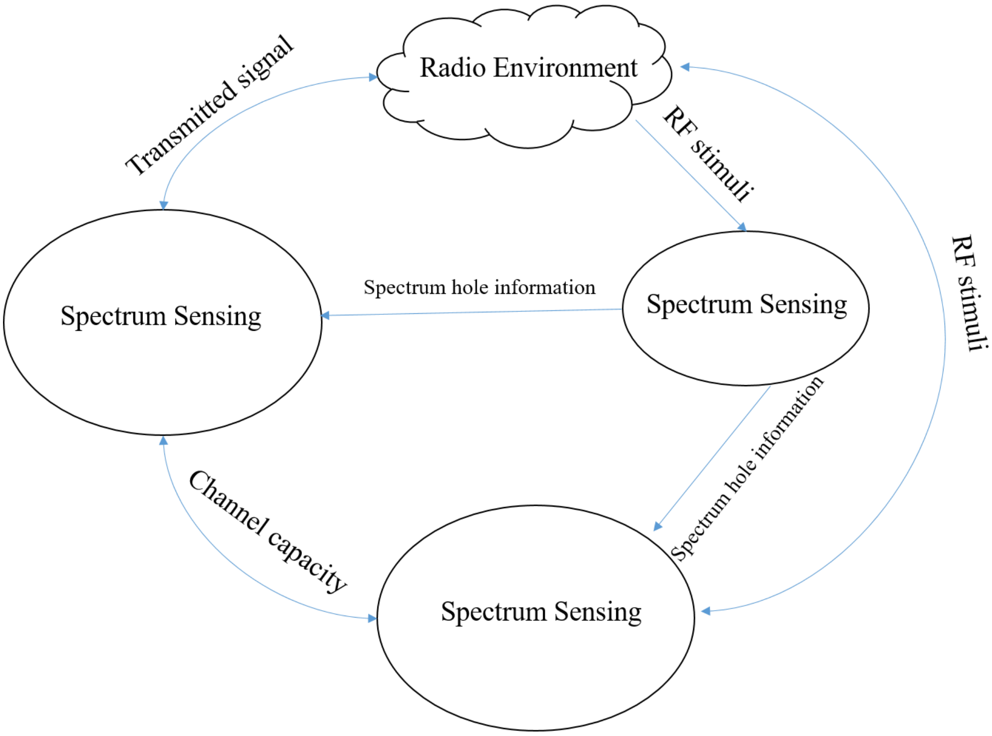

Figure 1.2 The cognitive cycle [3]

1.2.1 Spectrum Sensing

The SS function is responsible for the monitoring of the spectrum environment at the network node position, with the purpose of detecting unused spectrum, i.e. the SH. By sensing the spectrum the CR becomes aware and sensitive to the changes in its surrounding, giving to the CR the information needed to adapt to its environment. Spectrum Sensing is realized as a PHY and MAC mechanism [10, 11] and has been covered extensively in literature [7, 12, 13] and falls into the domain of the detection theory. While the PHY SS focus on the detection of signals, and the detection methods can be classified into two groups, either coherent (prior information needed, e.g. Pilot Detection, [7]) or non-coherent (no prior information needed, e.g. Energy Detector (ED), [14]). The MAC part of the SS focus on when to sense (in time) and which spectrum to sense (in frequency). The performance of the SS depends on the local channel conditions, i.e., depend on the multipath, shadowing and local interference. The conjunction of these conditions can result in regimes where the Signal to Noise Ratio (SNR) of the signal is below the detection threshold of the local detector, resulting in missed detections and in false alarms. To overcome this limitation the use of cooperation has been proposed. The focus of this thesis is on the CSS schemes, therefore further details about the background of these schemes is mentioned in Chapter 3.

1.2.2 Spectrum Analysis

The SH identified by the SS function has different characteristics which vary over time. The purpose of the SA function is to characterize these spectrum bands, as to identify the appropriate one for the CRN node requirements. To account for the dynamic nature of networks, each SH should consider not only the time-varying radio environment, but also the interferers activity and the spectrum band information such as operating frequency and bandwidth. Hence, it is essential to define characterizing parameters that can represent the quality of a particular spectrum band. The following are identified in [7]:

- Interference - The spectrum band in use determines the characteristics Path loss - The path loss increases as the operating frequency increases. If the transmission power of a node remains constant, then its transmission range decreases at higher frequencies.
- Link errors - Depending on the modulation scheme and the interference level of the spectrum band, the error rate of the channel changes.
- Link layer delay - Depending on the spectrum band in use, different path loss, wireless link error, and interference is expected. All these conditions amount to different link layer packet transmission delay.
- Holding Time - The activities of interferers can affect the channel quality of the network. Holding time refers to the expected time duration that the node can occupy a band before getting interrupted. The lower is the holding time the higher is the frequency of spectrum handoff. Since the spectrum handoff also means wasting time in adjusting the transmission to a new channel, the system throughput and connectivity are sacrificed in these procedures. So channels with longer holding times are better. Since frequent spectrum handoff can decrease the holding time, previous statistical patterns of handoff should be considered. The spectrum band is characterized by the channel capacity, which can be derived from the above parameters. The SNR is normally used to perform channel capacity estimation, but since it only considers the observation at the receiver, the previous parameters need also to be considered to estimate the channel capacity.

1.2.3 Spectrum Decision

Upon characterization of the available spectrum bands and the associated potential estimated channel capacity, the appropriate operating spectrum band can be selected. Based on the CRN node QoS requirements, the data rate, acceptable error rate, delay bound, transmission mode, and bandwidth can be determined. Then according to the decision rule in use, the set of appropriate spectrum bands can then be chosen. Several examples of rules that can be used in the SD function are reported in the literature. Some of them are highlighted in [15] where SD rules are presented, which are focused on fairness and communication cost, however assuming that all channels have similar throughput capacity. In [16], an opportunistic frequency channel skipping protocol is proposed for the search of channels with better quality, and where the decision is based on the channel SNR. In [17], an adaptive based centralized decision solution is presented, which also considers spectrum sharing. The adaptation mechanism considers the user traffic and the base station's hardware resources.

1.2.4 Spectrum Mobility

The purpose of the Spectrum Mobility function is to allow a network to use the spectrum in a dynamic manner, i.e. allowing the CR nodes to operate in the best available frequency band. The Spectrum Mobility function is defined as the process through which a CRN node changes its frequency of operation, also known as spectrum handoff [7]. In a CR network, the Spectrum Mobility arises when the conditions of the channel in use by the node become worse, due to the node movement or because an interferer appears in the channel. The Spectrum Mobility gives rise to a new type of handoff, referred to as spectrum handoff [7]. A CR can adapt to the frequency of operation. Therefore, each time a CR node changes its frequency of operation, the network protocols are going to shift from one mode of operation to another. The different layer protocols of the network stack need to adapt to the channel transmission parameters of the operating frequency, as well as being transparent to the spectrum handoff and the associated latency. The purpose of Spectrum Mobility management in CR networks is to make sure that such transitions are made smoothly and as soon as possible such that the applications running on a CRN node perceive minimum performance degradation during a spectrum handoff. It is therefore essential for the mobility management protocols to learn in advance about the duration of a spectrum handoff. This information can be provided by the SS and SA algorithms, through the estimation of the channel holding time. Once the mobility management protocols learn about this latency, their job is to make sure that the ongoing communication of a CRN node undergo only minimum performance degradation. Whenever a spectrum handoff occurs, there is an increase in latency, which directly affects the performance of the communication protocols. Thus, the main challenge in Spectrum Mobility is to reduce the latency for spectrum handoff, which is associated to the SS latency. During spectrum handoff, the channel parameters such as path loss, interference, wireless link error rate, and link layer delay are influenced by the dynamic use of the spectrum. On the other hand, the changes in the PHY and MAC channel parameters can initiate spectrum handoff. Moreover, the user application may request spectrum handoff to find a better quality spectrum band.

1.2.5 Spectrum Sharing

The shared nature of the wireless channel requires the coordination of transmission attempts between CRN nodes. Spectrum Sharing can be regarded to be similar to generic MAC problems in traditional systems. However, substantially different challenges exist for Spectrum Sharing in CR networks. The coexistence with other systems and the wide range of available spectrum are the main reasons for these unique challenges. In [7], an overview of the steps of Spectrum Sharing in CRN is provided. The Spectrum Sharing process consists of five steps:

- Spectrum sensing - When a CRN node aims to transmit packets, it first needs to be aware of the spectrum usage around its vicinity.
- Spectrum allocation - Based on the spectrum availability, the node can then allocate a channel. This allocation does not only depend on spectrum availability, but it is also determined based on existing spectrum access policies.
- Spectrum Access - Since there may be multiple CRN nodes trying to access the spectrum, this access should be coordinated in order to prevent multiple users colliding in overlapping portions of the spectrum.
- Transmitter-receiver handshake - Once a portion of the spectrum is determined for communication, the receiver should also be informed about the selected spectrum;
- Spectrum Mobility - When the conditions of the allocated spectrum deteriorate, the CRN nodes need to move to another vacant portion of the spectrum, making use of the spectrum mobility function.

The existing work in the literature regarding Spectrum Sharing can be classified on three aspects, based on the architecture, spectrum allocation behavior and on spectrum access technique.

The classification of spectrum sharing techniques based on the architecture is as follows:

- Centralized - A centralized entity controls the spectrum allocation and access procedures. To aid the procedures, a distributed sensing procedure is proposed such that each entity in the network forwards its measurements about the spectrum allocation to the central entity and this entity then constructs a spectrum allocation map. Examples of this kind of architecture can be found in [10, 17-22].

- Distributed - Distributed solutions are mainly proposed for cases where the construction of an infrastructure is not preferable. Each node is responsible for the spectrum allocation and access is based on local or global use policy. These policies can be vendor specific or can be dictated by an regulator entity, like the Federal Communications Commission (FCC). An example can be found in [23].

The classification of Spectrum Sharing techniques based on the access behavior are as follows:

- Cooperative - Cooperative solutions consider the effect of the node's communications on other nodes. The interference measurements of each node are shared with other nodes, and the spectrum allocation algorithms also consider this information. All centralized solutions are regarded as cooperative, although there are also distributed cooperative solutions. Examples of these can be found in [8, 18, 23-25].
- Non-Cooperative - Non-cooperative solutions consider only the node at hand. These solutions are also referred to as selfish. While non-cooperative solutions may result in reduced spectrum utilization, they do not require the exchange of control information among other nodes as the cooperative ones do. Examples of these can be found in [15, 26, 27].

When comparing these approaches in terms of architecture and access behavior, it is reported in the literature that cooperative approaches outperform non-cooperative ones, moreover distributed solutions closely follow centralized solutions. Evidence of these results are available in [27, 28].

The classification of spectrum sharing techniques based on the access technology are as follows:

- Overlay - In overlay spectrum sharing, a node accesses the network using a portion of the spectrum that is not used by licensed users. As a result, interference to the primary system is minimized, [19, 25, 28];
- Underlay -Underlay paradigm has the knowledge of the interference caused by all users. It mandates that concurrent primary and secondary systems transmission occur only if the interference generated by the SU at the PU is below some acceptable threshold. This technique requires sophisticated spread spectrum techniques and can use increased bandwidth when compared to overlay techniques.

The theoretical work on spectrum access in CRN reveals important trade-offs for the design of spectrum access protocols. It has been found that cooperative settings result in higher utilization of the spectrum as well as improved fairness. However, this advantage may eventually not be so high considering the cost of cooperation due to the signaling overhead. [29] reports that the spectrum access technique, whether it is overlay or underlay, always affects the performance of legacy systems. While an overlay technique focuses on the holes in the spectrum, dynamic spreading techniques are required for underlay for interference free operation between concurrent systems.

1.3 Physical Architecture and Re-configurability

The CR needs to be implemented on top of a hardware platform which enables its functionality. In Figure 1.3 a generic architecture of a CR transceiver is depicted, based on the one proposed in [8]. The main components of a CR transceiver are the radio front-end and the baseband processing unit. Each component can be reconfigured via a control bus to adapt to the time-varying Radio Frequency (RF) environment. In the RF front-end, the received signal is amplified, mixed and Analog to Digital (A2D) converted. The baseband processing unit of a CR is essentially similar to existing transceivers. The solution to enable this is the use of SDR platforms, an example of which currently available in the market is the hardware enabling the GNU radio software stack. While the functions mentioned before, i.e. SS, SA and SD, enable the cognitive capability, provide the spectrum awareness, whereas the re-configurability enables the radio to be dynamically programmed according to the radio environment. More specifically, the re-configurability is the capability of adjusting operation parameters for the transmission without any modifications on the hardware component. This capability enables the CRN node to easily adapt to the dynamic radio environment. In [7] one articulates what should be the main reconfigurable parameters to be implemented in the CR. These are as follows.

- Operating Frequency - Based on the radio environment information, the most suitable operating frequency can be determined, enabling the communication to be dynamically performed in the appropriate frequency;
- Modulation - A CRN node should reconfigure the modulation scheme in a way that is adaptive to the user requirements and channel conditions, i.e., in the case of delay sensitive applications, the data rate is more important than the error rate. Thus, the modulation scheme that enables the higher spectral efficiency should be selected. Conversely, the less sensitive applications require modulation schemes with low bit error rate.

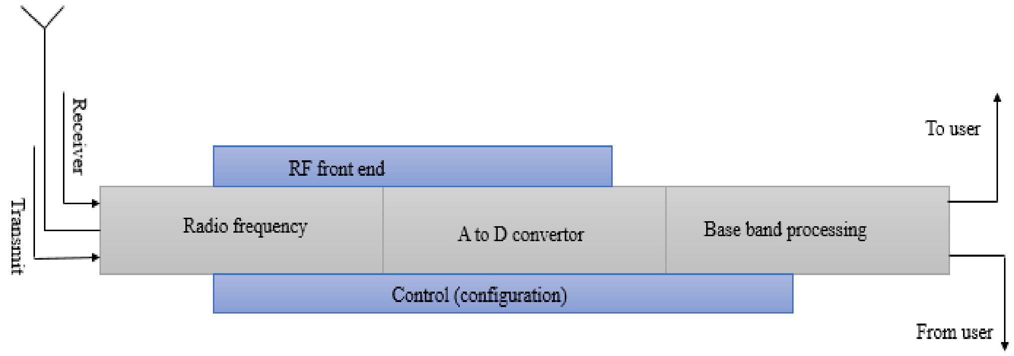

Figure 1.3 Cognitive radio transceiver [30]

- Transmission Power - Power control enables dynamic transmission power configuration within the permissible power limit. If higher power operation is not necessary, the CR reduces the transmitter power to a level that allows more users to share the spectrum, decreasing the interference;
- Communication Technology - A CR can also be used to provide interoperability among different communication systems, therefore employing the SDR capabilities. The transmission parameters of a CR can be reconfigured not only at the beginning, but also during a transmission. According to the spectrum characteristics, these parameters can be reconfigured such that the CR is switched to a different spectrum band, the transmitter and receiver parameters are reconfigured and the appropriate communication protocol parameters and modulation schemes are used. Such a re-configuration framework has been proposed in [30].

1.4 Typical Candidate Bands for Cognitive Radios

UHF bands, cellular bands, and fixed wireless access bands are the typical candidate bands for CR systems as follows.

- **UHF band:** The UHF band is currently used for TV broadcasting. In the broadcast television spectrum, the regulatory agency FCC has adopted policies [1] that allow the SU transmitter to operate at locations where the spectrum is not used by PU. The unused TV spectrum has been predicted to be one of the first spectrum ranges where innovative products and services using CR systems may appear [31].
- **Cellular bands:** Many cellular bands are centered around 800/900 MHz, 1.8/1.9 GHz, 2.1 GHz, 2.3 GHz, and 2.5 GHz. They are characterized by a ubiquitous coverage and

the communication is bidirectional. The cellular customers are mobile and the cell sites are generally in the same region as the CRs.

- **Fixed wireless access bands:** The fixed wireless access bands provide bidirectional broadband services and are centered around 2.5 GHz and 3.5 GHz. Wireless systems operating in these bands are very similar to cellular networks, except that the devices are not mobile in fixed wireless access bands. The devices are at fixed locations such as homes or businesses.

1.5 Potential Applications of CRN

Because CR is aware of the RF environment and is capable of adapting its transmission parameters to the RF spectrum environment, CR and the concepts of cognitive radio can be applied to a variety of wireless communication environment, especially in commercial and military applications. A few of applications are listed below:

- **Coexistence of wireless technologies:** CR techniques are primarily considered for reusing the spectrum that is currently allocated to the TV service. WRAN users can take advantage of broadband data delivery by the opportunistic usage of the underutilised spectrum. Additionally, the dynamic spectrum access techniques will play an important role in full interoperability and coexistence among diverse technologies for wireless networks. For example, CR concepts can be used to optimise and manage the spectrum when the wireless local area network (WLAN) and the Bluetooth devices coexist.
- **Military networks:** In military communications, bandwidth is often at a premium. By using CR concepts, military radios can not only achieve substantial spectral efficiency on a noninterfering basis, but also reduce implementation complexity for defining the spectrum allocation for each user. Furthermore, military radios can obtain benefits from the opportunistic spectrum access function supported by the CR. For example, the military radio can adapt their transmission parameters to use Global System for Mobile (GSM) bands, or other commercial bands when their original frequencies are jammed. The mechanism of spectrum management can help the military radio to achieve information superiority on the battlefield. Furthermore, from the soldiers' perspective, CR can help the soldiers to reach an objective through its situational awareness.
- **Heterogeneous wireless networks:** From a user's point of view, a CR device can dynamically discover information about access networks, e.g. WiFi and GSM, and makes decisions on which access network is most suitable for its requirements and

preferences. Then the CR device will reconfigure itself to connect to the best access network. When the environmental conditions change, the CR device can adapt to these changes. The information as seen by the CR user is as transparent as possible to changes in the communication environment.

1.6 Cognitive Radio Wireless Sensor Networks (CR-WSN):

A wireless sensor network (WSN) is a wireless network consisting of spatially distributed autonomous devices using sensors to monitor physical or environmental conditions. A WSN system incorporates a gateway that provides wireless connectivity back to the wired world and distributed nodes. The wireless protocol selected depends on the application requirements. Some of the available standards include 2.4 GHz radio based on either IEEE 802.15.4 or IEEE 802.11. CR-WSN is defined as a distributed network of wireless CR wireless sensor (CRWS) nodes, which sense an event signal and collaboratively communicate their readings dynamically over the available spectrum bands in a multi-hop manner, ultimately to satisfy the application-specific requirements. In CR-WSNs, a wireless sensor node selects the most appropriate channel once an idle channel is identified and vacates the channel when the arrival of a licensed user on the channel is detected. The CR technique is probably one of the most promising technique for improving the efficiency of the WSNs. CR-WSNs increase spectrum utilization, and fulfils the end-to-end goal, increase network efficiency and extend the lifetime of WSNs.

1.6.1 Potential Application Areas of CR-WSNs

CR-WSNs may have a wide range of application domains. Indeed, CR-WSN can be deployed anywhere in place of WSNs. Some examples of prospective areas where CR-WSNs can be deployed are as follows: facility management, machine surveillance and preventive maintenance, precision agriculture, medicine and health, logistics, object tracking, telemetries, intelligent roadside, security, actuation and maintenance of complex systems, monitoring of indoor and outdoor environments. Following are some potential applications of CR-WSN.

- Military and Public Security Applications
- Health Care
- Home Appliances and Indoor Applications
- Bandwidth-Intensive Applications
- Real-Time Surveillance Applications
- Transportation and Vehicular Networks

1.7 Motivation

The main focus in this thesis is on improvement of detection and EE performance of CSS in a CRN. The motivation to focus only on this aspect of CR comes from that the SS is the key mechanism to enable spectrum awareness, without which all the other CR functions cannot operate. So as referred before: CR [2, 4] has emerged as a technology which allows the access on the intermittent periods of unoccupied frequency bands, SH, and therefore increasing the spectral efficiency.

To allow this opportunistic access, the CRN nodes must be able to detect the presence of the licensed nodes in a monitored range of spectrum, also known in the literature as PU. This is accomplished by the SS, where the CRN node samples the targeted spectrum and based on those samples decides whether an incumbent signal is present or not. The purpose of SS, besides detecting available resources, is also to limit the interference that the CRN nodes may cause in the incumbent. Therefore the detection performance of the SS scheme in use by the CR nodes is crucial to the performance of both CRN as well as the incumbent network, may it be licensed or not.

The performance of detector used in the spectrum sensing mechanism is given by:

- **Probability of False Alarm**, P_f - which quantifies the probability of a CR user declaring that a incumbent is present in the spectrum when the spectrum is not. The occurence of a false alarm will reduce the spectral efficiency, since spectrum resources are identified as occupied when they are in fact available to be used.
- **Probability of Detection**, P_d - which quantifies the probability of a CR user detecting that a incumbent is present. When a miss detection occurs the CRN node will most likely try to use the identified resource, and therefore the incumbent will be interfered.

The P_f and P_d can be expressed as function of the other, and therefore a common practice when designing a detector for optimal detection performance, the P_d is maximized while subject to the constraint of the P_f.

The performance of the flat network may degrade once the size of the network increases. This is because of the fact that increasing the network size and control overhead in the network also leads to the relevant increases. Clustering is one of the widely investigated solutions to scale down the large flat sensor network and to make the network operations more efficient. In clustering, the network is organized into logical groups, which depend on network characteristics and application requirements. Cluster-based networks has various advantages as compared to flat network as follows:

- More Scalability
- Less Load
- Less Energy Consumption
- More Robustness
- Collision Avoidance
- Latency Reduction
- Load Balancing
- Maximizing of the Network Lifetime

In this thesis cluster based cooperative spectrum sensing (CBCSS) has been investigated. CBCSS scheme with different fusion rule is proposed. In the first part detection accuracy of energy detector, based CBCSS is discussed over different fading channels. In the second part EE performance of non-cluster and cluster based CSS is discussed.

1.8 Problem Definition

The problem tackled in this thesis is to develop a CSS mechanism which both overcomes both the hidden node problem, at the same time is Energy Efficient and allows to monitor several frequency channels. With that in mind the problem tackled can be expressed through the following questions:

- How to measure the performance of CSS over different fading conditions like Rayleigh, Nakagami and Rician fading channel.
- How to measure performance of Cluster based centralised and distributed CSS on different environment conditions.
- How intra cluster and inter cluster fusion rule affects detection performance of CSS.
- How to calculate EE for cluster based CSS and optimize EE, taking in to consideration the number of cooperative users, fusion rule, transmission power and sensing time.
- How to determine the joint optimal parameters that maximizes the EE in the cluster-based CSS through iterative methods**.**

In this thesis, each one of the question is analyzed and answered.

1.9 Original Contributions

The original contributions are as follows:

- **The first contribution** is the performance evaluation of Cluster based CSS over Rayleigh, Rician and Nakagami fading channels. The performance is compared with the non-clustered centralised CSS scheme. A cluster based design model is proposed with inter and intra fusion rules with better detection probability. The detection probability and false alarm probabilities are derived for the proposed model. The performance improvement is achieved in the proposed work by employing diversity combining techniques.

- **The second contribution** is the performance measurement of EE of SUs in cluster-based CSS with four different fusion rules. Optimum fusion rule, which maximizes the EE in cluster-based CSS is determined. Effect of total number of users and number of clusters over EE is also investigated.
- **The third contribution** : An iterative algorithm is proposed which determines the number of users and number of clusters that maximizes the EE in cluster based CSS. For CSS, effect of varying the fusion rule threshold on the optimal sensing duration that maximizes the EE has been investigated and its corresponding detection probability is studied. An iterative algorithm is proposed for this joint optimization**.**
- **The fourth contribution** is the iterative algorithm that is proposed to determines the joint optimal sensing time, transmission power that maximizes the EE in the cluster-based CSS. Proposed CSS is investigated on practical sensing channel considering error probability. PU traffic is also considered in the optimization problem

The publications done during the Ph.D. work which are directly related to the work contributed in this thesis are also listed in the list of publications.

1.10 Thesis Outline

The outline of the thesis is as follow:

In **Chapter 1**, an overview on the CR fundamentals and its functionality, together with the motivation for the work developed and described in the thesis, the problem definition and the original contributions is given.

In **Chapter 2** literature review of related work has been done. The previous work related to non-cooperative spectrum sensing, CSS, cluster based CSS and Energy Efficient CSS has been discussed and compared.

In **Chapter 3**, spectrum sensing overview is discussed. Where common spectrum sensing methods are highlighted, how the local decisions of the local detectors are reported to the network, how the local decisions can be combined to achieve network wide decisions in CSS is discussed. Diversity combining techniques are also presented in this chapter.

In **Chapter 4**, cluster based CSS over different fading channels is presented. Cluster based CSS with four fusion rules OR-OR, AND-AND, AND-OR and OR-AND has been investigated over Rayleigh, Rician and Nakagami fading channels. Further diversity combining techniques are used to improve the detection performance of cluster based CSS. The chapter concludes with OR-OR fusion rule of distributed CSS outperforms the other fusion rules and it performs better then centralised CSS.

In **Chapter 5**, EE of the CSS is determined. In this chapter, an iterative algorithm is proposed to determine joint optimal fusion rule threshold and sensing time that maximizes the EE of CSS. The chapter concludes that there is an optimal value of fusion rule threshold and sensing time at which the EE is maximum.

In **Chapter 6**, effect of fusion rule on EE is investigated for centralized CSS and a cluster-based CSS which have been proposed with four fusion rules OR-OR, AND-OR, OR-AND, AND-AND. These are investigated from EE point of view. An iterative algorithm is proposed which finds the optimum number of clusters and number of users in a cluster, which maximizes the EE.

In **Chapter 7**, optimized fusion rule is determined that maximizes the EE for cluster based CSS. For the proposed CSS, joint optimal sensing time and transmission power of energy efficient CSS is determined. The joint optimization design problem is formulated as function of sensing time and transmission power subjected to PU protection constraints. An iterative algorithm is proposed to determine joint optimal sensing time and transmission power that maximizes the EE of CSS.

Finally in **Chapter 8** the conclusion and outlook for future work has been discussed.

CHAPTER 2: REVIEW OF LITERATURE

This chapter presents the review of the related work carried out in this thesis. The previous CR work is divided in three categories. 1. General spectrum sensing. 2. Cooperative spectrum sensing. 3. EE in CSS.

2.1 Spectrum Sensing

In recent time, plenty of research has been done in spectrum sensing using detection schemes. Energy detection method has been investigated by Sonnenschein *et al*. 1992, Kostylev 2002, Digham, Alouini *et al*. 2003 [32-34]. Matched filter detection is discussed by Haykin, Thomson *et al*. 2009, Ma, Li *et al*. 2009, Zeng, Liang *et al*. 2010 [35-37]. Cyclostationary feature detection is discussed by Gardner 1988, Dandawate and Giannakis 1994, Sutton, Nolan *et al*. 2008 [38-40], and co-variance matrix based detection is investigated by, Zeng *et al*. 2007, Zeng and Liang 2009, Font-Segura *et al*. 2010 [41-44]. Co-variance detection using multiple antennas at receiver is presented in Wang, Fang *et al*. 2010 [45]. In the presence of unknown noise multi antenna detector is proposed by López-Valcarce, Vazquez-Vilar *et al*. 2010 [46]. The author Zhang, Qiu *et al*. 2011 [47] proposed a feature template matching which extracts signal features as eigenvector of signals covariance matrix. For non-white wide sense stationary signal, this feature is stable. For white noise Hou and Qiu 2014 [48] proposed a detection method. Linear feature template matching is extended to nonlinear feature template matching by Ding, Wu *et al*. 2013 [49] using mapping data from input to the high dimension feature space. Umme Salama *et al*. 2018 [50] proposed an algorithm that attains results from a matched filter and implements it within the energy detector, and analyzes the signals over a channel of Additive White Gaussian Noise (AWGN) for a range of Signal-to-noise ratios (SNRs).

2.1.1 Cooperative Spectrum Sensing

Hidden terminal problem occurs when the SU is shadowed or in multipath fading. In this case, SU cannot detect the presence of PU due to low SNR of the received signal. The SU then assume that the frequency band is vacant and begins to access the band without noticing the presence of PU. To solve this issue, multiple SUs coordinated to perform spectrum sensing cooperatively. CSS can increase the probability of detection in fading channels [9, 51].

Recently CSS based on censored energy detector has been investigated by Bouraoui and Besbes 2016 [52] with different fusion rule performances. CSS with diversity reception is described by Sun, Nallanathan *et al*. 2011 and Nallagonda, Roy *et al*. 2016 [53, 54] Hard and soft fusion schemes for CSS over noisy reporting is considered by Sakran and Shokair 2013 [55]. The analytical expressions are derived in [55] for hard and soft one bit and two bits combination schemes for CSS. A double threshold ED based CSS is proposed by Bhowmick, Nallagonda *et al*. 2015 [56]. In this paper a combination of hard and soft fusion based hybrid censoring is investigated. To mitigate the effect of noise uncertainty a double dynamic threshold method is used by Farag and Mohamed 2015 [57, 58].

Smriti *et al*. 2018 [59] propose a CSS along with double threshold detection method which considers the previous sensing history and two thresholds are considered and compared to a test statistic and accordingly a decision regarding the presence and absence of the PU is made. Fang Ye *et al*. 2018 [60] proposed a novel CSS algorithm based on node filtrating (NF-CSS) avoiding low SNR nodes being involved in the collaboration by decreasing the number of nodes.

Anastassia Gharib *et al*. 2018 [61] proposed a distributed learning-based multi-band multi-user cooperative spectrum sensing (M2CSS) scheme to select most appropriate SUs to sense channels. The proposed M2CSS scheme can enhance detection performance, avoid the choice of redundant cooperative SUs, owning similar sensed information, and provide fair energy consumption for all channels compared to the existing schemes. J. H. Kim *et al*. 2019 [62] proposed a machine learning based CSSs in which Kullback-Leibler Divergence based, analytical expressions for the spectrum sensing coverage of a single SN are derived and also proposed a strategy on how to place a few sensing nodes to cover the whole area of the PU.

Banavathu *et al*. 2019 [63] formulated a generalized optimal fusion problem (GOFP) to optimize the N out-of-K rule for the Bayesian test and then solve the GOFP to obtain the optimal value of N. The smallest number of CUs required in CSS is obtained while satisfying a target error bound at the FC. Distributed CSS is investigated by Yu, Huang *et al*. 2010 [64] where biology based spectrum sensing is suggested in which final decision are made on the basis of consensus. A decentralized CSS is studied by Lo and Akyildiz 2010 [65]. In the proposed method past sensing results are used to sense the channel.

2.1.2 CSS with Diversity Schemes:

The average detection probability and false alarm probability using energy detector is derived for diversity reception schemes by Sun, Nallanathan *et al*. 2011 [53]. Also in [53] the performance of diversity combining techniques are compared to find a proper cooperative strategy under different constraints. Nallagonda, Roy *et al*. 2016 [54] improved energy detector (IED) based CSS with multiple antennas and selection combining is investigated over noisy and faded sensing channels.

Transmit diversity using orthogonal Space time block codes (STBC) over non selective Nakagami fading is analysed by Maaref and Aissa 2006 [66]. Bai, Wang *et al*. 2014 [67] employed transmit diversity by CSS to improve the performance of decision reporting. STBC schemes is considered in the reporting channel between CR user and base station with time division multiple access method by Bai, Wang *et al*. 2014 [67].

2.1.3 CSS over Imperfect Reporting:

CSS over imperfect reporting is investigated by Li, Zhao *et al*. 2010, Singh, Bhatnagar *et al*. 2011, Wang, Wei *et al*. 2013 [68-70]. The performance of CSS is optimized with improved energy detector over imperfect reporting channel by Singh, Bhatnagar *et al*. 2011 [68]. In addition, in [68] the expression for total error rate of detection for CSS is derived and optimal number of CR users required are obtained by minimizing the total error rate.

Sensing performance of CSS over imperfect reporting is analysed by Wang, Wei *et al*. 2013 [69] and optimal fusion rule threshold is determined for K out of N rule. Li, Zhao *et al*. 2010 [70] proposed a practical reporting approach in CSS, called listen before reporting, which consider both the availability and reliability of the reporting channels.

Meiling Li *et al*. 2019 [71] proposed a Censor-Based CSS (C-CSS) with Multi-Antenna. It is shown that the C-CSS approach provides two distinct benefits compared with the conventional sensing approach, i.e., without censoring: i) the sensing tail problem, which exists in imperfect sensing environments, can be mitigated; ii) less SUs are ultimately required to obtain higher secondary throughput.

2.1.4 CSS over Fading Channels.

Singh, Bhatnagar *et al*. 2012 [72] proposed an energy detection based CSS with multiple antennas at each CR over Rayleigh fading channel. An improved energy detector based multiple antenna CR system is analysed by Nallagonda, Chandra *et al*. 2013 [73] over Rician and Hoyt fading channel. However, in [73] detection performance based on optimal parameters is not studied.

An improved energy detection based optimized CSS is investigated by Ranjeeth, Behera *et al*. 2016 [74] over AWGN and Rayleigh fading channel. Verma, Soni *et al*. 2018 [75] proposed energy detection based CR sensing is over Nakagami fading and MRC diversity reception. However, the work in [75] is limited to single CR user in non-cooperative scenario. He Huang *et al*. 2018 [76] proposed CSS with diversity to improve the detection accuracy and mitigate the shadowed fading features with OR-rule. It show that the detection capacity of ED will be evidently affected by α-κ-μ fading channel. An improved energy detection based optimized CSS is proposed by Ranjeeth, Nallagonda *et al*. 2017 [77] over Nakagami and Weibull fading channel. In [77] reporting channel is considered to be ideal.

Sharma and Sharma 2017 [78] proposed a distributed and centralised CSS comparison over different fading channels. Nakagami is a general fading model proposed by Nakagami 1960 [79]. It is suitable for the land and indoor mobile applications [79-81]. However, CSS in presence of Nakagami fading scenario is less studied. Moreover, the CR users may be mobile in some applications. In such cases, channel estimation is costly. Therefore, CSS over Nakagami fading for a wide range of SNR and different decision fusion is useful for the system design.

Table 2:1 Summary of previous CSS work

Work	Adopted approach	Performance metric	Channel fading	Noisy reporting considered	Diversity Reception
[Yu, Huang *et al*. 2010]	Distributed CSS	False alarm (P_f) & detection probability(P_d)	No	No	No
[Lo and Akyildiz 2010]	Reinforcement Learning based CSS	P_f, P_d, Receiver operating characteristics (ROC)	No	No	No

[Singh, Bhatnagar *et al*. 2012]	Multiple Antenna Based CSS	Total error rate, P_f, P_d,	Rayleigh	Yes	Selection combining (SC)
[Nallagonda, Chandra *et al*. 2013]	Improved energy detector based CSS	Total error rate	Hoyt and Rician	No	No
[Ranjeeth, Behera *et al*. 2016]	Improved energy detection based CSS	Optimal users (Nopt.)	Rayleigh	Yes	Selection diversity
[Verma, Soni *et al*. 2018]	CSS	Total error rate, Complimentary ROC	Nakagami	No	Maximum ratio combining
[Ranjeeth, Nallagonda *et al*. 2017]	CSS	Total error rate, P_f, P_d,	Nakagami, Weibull	Yes	No

2.1.5 Cluster based CSS:

Cluster-based CSS has been first proposed by Sun, Zhang *et al*. 2007 [82] and a cluster-based CSS under bandwidth constraints were discussed by Bai, Wang *et al*. 2010 [83]. Lee and Wolf 2008, Wang, Feng *et al*. 2009 [84, 85] proposed a method in which the CR users are grouped into small clusters, and each CR user sends the sensing information to the cluster head (CH). The CH transmits the information to the FC, but before that, it may compress the sensing information.

Kozal, Merabti *et al*. 2014 [86] proposed a multi-level cluster based CR. In [86] the cluster head (CH) that are far away from FC can forward their decision to the near cluster head rather than FC. Xia, Wang *et al*. 2009 [87] proposed a method in which CR nodes are separated into clusters, and report local decisions to CH to make cluster decisions through a data fusion method.

TepeAbeer F *et al*. 2018 [88] proposed an adaptive threshold energy efficient multi-level hierarchical cluster-based cooperative spectrum sensing (MH-CBCSS) algorithm with low computational complexity. The proposed algorithm enables a CR to dynamically adapt its detection threshold to meet the target overall detection error rate. Yonghua Wang *et al*. 2018

[89] proposed a CSS method based on a feature and clustering algorithm in the case of a small number of SUs participating in CSS. This method introduces order decomposition and recombination and interval decomposition and recombination based on stochastic matrix, which can increases the SUs logically.

2.2 Energy Efficiency in CSS:

Cooperative spectrum sensing can mitigate effects due to non cooperative spectrum sensing, but it requires more energy consumption and sensing time due to large overhead. The EE is a comprehensive metric, which represents the overall performance of the CR because it jointly takes account of achievable throughput, detection accuracy, and overall energy consumption. The EE is defined as the rate of data transmission per unit energy.

Many work reported in the literature use the concept of minimizing the energy consumption in order to maximize the EE. Lunden, Koivunen *et al*. 2007, Sun, Zhang *et al*. 2007 [85, 90, 91] used the censoring technique in which only those CR users with reliable sensing information will send the information to the FC. Hence, the energy consumption during transmitting sensing information from CR user to FC reduces. Liu, Li *et al*. 2017 [92] investigated a simultaneous CSS and energy harvesting model to improve the performance of multichannel CR system. A periodic CSS model based on weight fusion is given by Liu, Jia *et al*. 2013[93] in which sensing period and searching time are optimized.

Some authors considered throughput as performance metric and try to find the balance between maximization of sensing accuracy and throughput as by Liang, Zeng *et al*. 2007, Peh, Liang *et al*. 2009, Tang, Chen *et al*. 2011 [94-96]. Liang, Zeng *et al*. 2007 [94] investigated a sensing-throughput tradeoff problem and throughput is maximized at optimum sensing duration. Sensing -throughput tradeoff for CSS is presented by Peh, Liang *et al*. 2009 [95] where optimum sensing duration and fusion rule threshold is determined for maximum throughput. A more realistic case is considered by Tang, Chen *et al*. 2011[96], which includes the effect of PU traffic. Throughput is the performance metric in the work [94-96]. However, EE is considered to be the comprehensive metric that is able to represent the overall performance of CR because it jointly takes account of the throughput, total energy consumption and detection accuracy.

EE is examined as performance metric in [97-106]. Gao, Xu *et al*. 2013 [97] proposed a joint optimization of number of SUs, detector threshold and sensing time to maximize the EE. In [97], AND fusion rule is used to determine EE. However, for AND fusion, detection probability is low compared to other fusion rules. Hu, Zhang *et al*. 2016 [98] proposed a spectrum efficiency (SE) along with EE as performance metric. In [98] the SE-EE tradeoff for CSS is investigated and both SE and EE are optimized via joint optimization of sensing time and detector threshold. However, the work in [98] does not give the detailed explanation whether the optimal design parameters satisfy the detection accuracy and false alarm constraints. Das and Das 2017[99] solved the EE maximization problem in double threshold based soft fusion CSS. In this paper, authors have proposed an iterative algorithm called Dinkelbach method to jointly optimize transmission power and sensing time and finally Lagrangian duality theorem is used to calculate exact power allocated to each SU. Das, Bhowmick *et al*. 2017[100] investigated an improved energy detector based CSS which jointly optimizes the sensing time and signal power raise factor (SPRF). Optimal values of SPRF and sensing time are calculated for maximum throughput and maximum harvested energy. Wu and Tsang 2011 [101] considered maximization of EE of single CR with optimization of sensing time under various scenario. The work in [101] also studied the sensing and transmission power relationship with optimal sensing time.

Shi, Teh *et al*. 2013 [102]considered joint optimization of sensing and transmission time that maximize the EE. The work by Zhang, Xiao *et al*. 2016 [103] reports joint optimal sensing time and transmission power to maximize the EE for single CR user. Qiu, Xu *et al*. 2011 [104] proposed an algorithm using golden search method to determine the optimal transmission power that maximizes the EE under hybrid spectrum sharing scenario. An adaptive algorithm for optimal power allocation that maximizes the EE of an OFDM based system under transmission power and maximum interference level constraints is proposed by Wang, Xu *et al*. 2012 [105]. An iterative algorithm is proposed by Ozcan and Gursoy 2014 [106] to determine the optimal power allocation that maximizes the EE subject to interference constraint. However, none of the works in [104-106] considering determining the optimal sensing duration for the Energy Efficient CR.

Table 2:2 Summary of previous works in Energy Efficiency in CSS

Work	Adopted approach	Fusion scheme	Performance Metric	Optimal parameter	Does noisy reporting consider?
[Liang, Zeng *et al*. 2007, Peh, Liang *et al*. 2009, Tang, Chen *et al*. 2011]	Sensing-throughput tradeoff	OR, AND, Maj.	Throughput	Sensing duration and fusion rule	No
[Gao, Xu *et al*. 2013]	Energy efficient CSS	AND	EE	Detector threshold, number of users, sensing time	No
[Hu, Zhang *et al*. 2016]	Joint optimization for SE-EE tradeoff	k-out of -N	EE	Detector threshold, sensing time	No
[Das and Das 2017]	Dinkelbach method-based iterative power adaptation algorithm	Non-cooperative	EE	Transmit power, sensing time	No
[Das, Bhowmick *et al*. 2017]	improved energy detector based CSS	Non-cooperative	throughput	Sensing time and signal power raise factor	No
[Wu and Tsang 2011]	Joint optimization of Sensing and Transmission Durations	Non-cooperative	EE	Sensing and Transmission Durations	No
[Shi, Teh *et al*. 2013]	Sub-Optimal Algorithm for Joint optimization of Sensing and Transmission Durations	Non-cooperative	EE	Sensing and Transmission Durations	No

[Zhang, Xiao *et al*. 2016]	Linear search and Iterative-based Algorithm to optimize sensing duration and the transmit power	Non-cooperative	EE	Sensing duration and the transmit power	No
[Qiu, Xu *et al*. 2011]	Modified golden section iterative search	Non-cooperative	EE	Transmit power	No
[Wang, Xu *et al*. 2012]	Dual Bisection Search	Non-cooperative	EE	Transmit power	No
[Ozcan and Gursoy 2014]	Dinkelbach's method-based power adaptation	Non-cooperative	EE	Transmit power	No
[Peh, Liang *et al*. 2011]	Bisection algorithm for joint fusion rule and detector threshold optimization	k-out of -N	EE	Fusion rule and detector threshold	No
[Awin, Abdel-Raheem *et al*. 2017]	Bisection algorithm for joint Sensing duration and Transmission power optimization	Non-cooperative	EE	Sensing duration and Transmission power	No
[Zhang, Nie *et al*. 2017]	Imperfect Hybrid Spectrum Sensing	Non-cooperative	EE	Sensing Time and Power Control	No
[Khasawneh, Agarwal *et al*. 2012]	Cluster based CSS	Non-cooperative	EE	Power consumption ratio, number of clusters	No
[Rauniyar and Shin 2015]	Cluster based CSS	Non-cooperative	EE	Number of CR nodes, number of packets to FC	No

[Muthukkumar and Manimegalai 2017]	Distributed dynamic load balanced clustering	Non-cooperative	EE	Number of clusters, average energy consumption for clusters	No

Peh, Liang *et al*. 2011 [107] considered optimizing the fusion rule threshold and sensing threshold to maximize the EE. However, the detection probability at the optimal sensing and fusion rule threshold is lower than that desired. Joint optimization of sensing time and transmission power is investigated by Awin, Abdel-Raheem *et al*. 2017 [108]. In this study, a bisection algorithm of low complexity is proposed to determine optimal sensing time and transmission power. The work in [108] is proposed for non-cooperative spectrum sensing. Sensing time optimization for imperfect hybrid spectrum sensing is investigated by Zhang, Nie *et al*. 2017 [109]. In this study optimization problem is solved in asymptotically optimal manner.

Fu Jiang *et al*. 2018 [110] proposed an RF energy harvesting cognitive radio network (CRN) in which cooperating SUs are equipped with energy harvesting capabilities. The SUs can harvest energy by converting the received radio frequency (RF) signal into electricity. Subhankar Chatterjee *et al*. 2019 [111] proposed an Energy Harvesting Cooperative CRN in which SUs are clustered into two groups and function in a way that when the SUs in Group I participate in cooperative SS, the SU nodes in Group II harvest energy from the radio frequency (RF) signal of PU .

2.2.1 Energy Efficiency in Cluster based CSS:

Khasawneh, Agarwal *et al*. 2012[112] considered a method in which censoring and clustering are combined in single Energy Efficient algorithm for the noisy reporting channel. Rauniyar and Shin 2015 [113] proposed a novel Energy Efficient clustering, based on CSS for CR networks. The proposed scheme in [113] utilizes the concept of pairing among sensor nodes and switches between Awake and Sleep modes for EE. Muthukkumar and Manimegalai 2017[114] proposed a distributed dynamic load balanced clustering algorithm. In [114] each node in the cluster calculate the, residual energy, cooperative gain, distance, and sensing cost from the neighboring clusters to perform the optimal decision.

2.3 Research Gap

It is clear that efforts have been made to improve the performance of CSS. However, it is also evident that none of the literature is available to the best of our knowledge that determines the detection performance of cluster based distributed CSS over Rayleigh, Nakagami and Rician fading channel with respect to intra and inter fusion rules. In addition to that clustering can improve the performance of CSS. There are lot of advantages of clustering e.g. Scalability, data aggregation, reduced energy consumption etc. but there is always a control overhead in a clustered network which is closely related to different network parameters, e.g. node mobility, node transmission range, network size, and network density. Again, a trade-off is there between gain and overhead that will be always there in any network designing. However, some researchers have come up with Control Overhead Reduction Algorithms (CORA), which aims to reduce the control overhead messages in a clustered topology.

In cluster based CSS there will be some control and reporting overhead. In CSS itself if the number of SUs are increased, it will surely improve the detection probability but cooperative SUs overhead also increases. Thus, the trade-off between reporting overhead and achievable throughput of the SUs becomes an important research aspect. The EE is a comprehensive metric, which represents the overall performance of the CR because it jointly takes account of achievable throughput, detection accuracy, and overall energy consumption.

Many research papers in literature are available, which determines the EE of CSS and optimizes the EE based on different parameters but none is available which measures the performance of Cluster based CSS with respect to inter and intra fusion rules and jointly optimizes the sensing time and transmission power. Thus, this analytical study becomes relevant and helps in deciding which fusion rule is appropriate and what should be number of clusters and number of SUs in a cluster through which maximum EE can be achieved. The work reported in this thesis focus on these aspects.

Next chapter deals with the overview of spectrum sensing in CRN. Non-cooperative and CSS methods have been investigated over Rayleigh fading environment for practical reporting channel.

CHAPTER 3: SPECTRUM SENSING IN CRN-AN OVERVIEW

The SU need to detect the presence of vacate spectrum in the neighboring network. These vacate spectrum are known as spectrum holes (SH) or white spaces. It should be able to quit the frequency band when PU starts communicating. This process is called spectrum sensing. Spectrum sensing is the first step to implement CR network [6]. In this chapter various spectrum sensing methods have been explained.

To identify the presence of PU, various spectrum sensing techniques are proposed in recent years. Most of the spectrum sensing techniques is classified as non-cooperative detection and cooperative detection.

3.1 Non-Cooperative Spectrum Sensing:

In this type of spectrum sensing, CR acts on its own. It is also known as single user sensing. In non-cooperative spectrum sensing there is no user cooperation between SUs as shown in Figure 3.1.

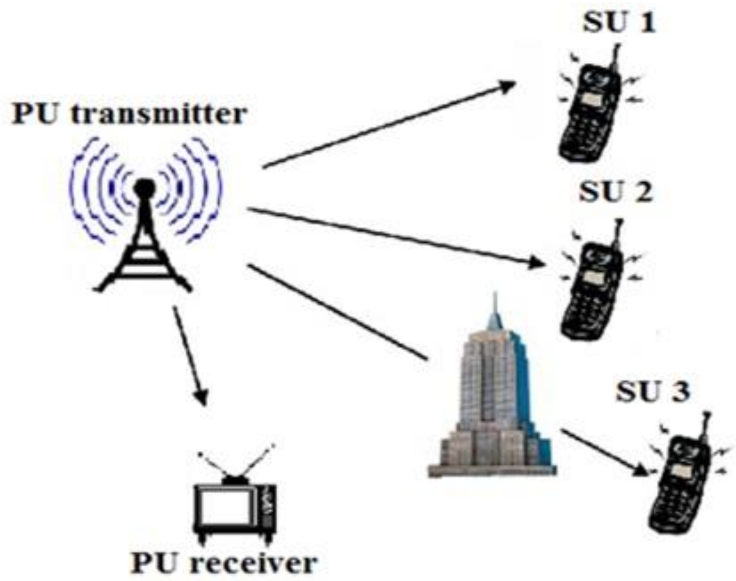

Figure 3.1 Non-cooperative spectrum sensing scenario [91]

It may further be classified as:

3.1.1 Energy Detector Sensing:

The most common type of spectrum sensing is the energy detector (ED) due to its simple implementation. It does not require a priori knowledge about the PU, and the detector requires only a short detection time. The signal is detected from a comparison of the energy detector output with a threshold that depends on the noise floor [14].

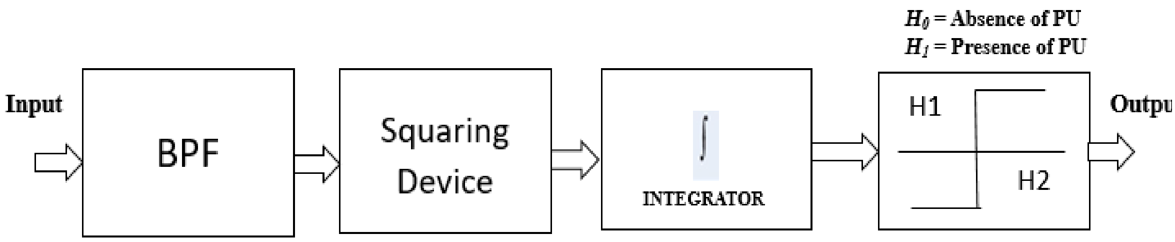

Figure 3.2 Energy detector block diagram [14]

The block diagram of an energy detector is shown in Figure 3.2. It receives a signal s(t) at the input and gives a binary decision regarding the presence of the PU. It may be modelled as

$$z(t) \triangleq \begin{cases} n(t), & : \ H_0 \\ hs(t) + n(t), & : \ H_1 \end{cases} \tag{3.1}$$

where s(t) and n(t) is the unknown transmitted signal and additive noise signal respectively and h is the fading co-efficient if the channel. H_1 and H_0 refers to the presence and absence of the signal respectively.

In ED, signal z(t) is filtered, squared and integrated to yield a decision variable Z which may be represented as

$$Z = c \int |z(t)|^2 dt, \tag{3.2}$$

here c is a constant. The decision variable Z can be approximated by using sampling theorem representation of bandlimited signal as sum of squares of random variables. The variable Z has central and non-central chi square distribution under H_0 and H_1 respectively. Thus, PDF of Z for H_0 and H_1 can be written as

$$f_Z(z) = \begin{cases} \frac{1}{2^u \Gamma(u)} \ z^{u-1} e^{-\frac{z}{2}} & : \ H_0 \\ \frac{1}{2}\left(\frac{z}{2\Upsilon}\right)^{\frac{u-1}{2}} \ e^{-\frac{2\Upsilon+z}{2}} \ I_{u-1}\left(\sqrt{2\Upsilon z}\right), & : \ H_1 \end{cases} \tag{3.3}$$

where $I_r(.)$ is the rth order Bessel function, Γ(.) is the gamma function. The signal to noise ratio of secondary transmission is defined by $\Upsilon = |h|^2 \frac{E_z}{N_0}$ where E_z and N_0 is the signal energy and noise power respectively, u is the time bandwidth product. It is assumed that there is a single PU and the distances between the CRs are small compared with the PUs. Therefor each channel gain has same variance and average SNR is same at each CR. If λ is the detector threshold, the false alarm and detection probability for AWGN fading channels are given by [34]

$$P_f = \frac{\Gamma\left(u, \frac{\lambda}{2}\right)}{\Gamma(u)} \tag{3.4}$$

$$P_d = Q_u\left(\sqrt{2\Upsilon}, \sqrt{\lambda}\right), \tag{3.5}$$

where $Q_u(.,.)$ is generalized Marcum Q function. For Rayleigh distribution, probability of detection is given as [34] :-

$$P_{d^{ray}} = \frac{1}{1+\Upsilon} \sum_{n=1}^{u-1} \left(\frac{\lambda}{2}\right)^n \frac{exp\left(-\lambda/_2\right)}{n!} \, {}_1F_1\left[1; n+1; \frac{\Upsilon\lambda}{2(1+\Upsilon)}\right] + exp\left[-\frac{\lambda}{2(1+\Upsilon)}\right], \tag{3.6}$$

where ${}_1F_1$ (. ;.;.) denotes confluent hypergeometric function.

3.1.2 Cyclostationary-Based Sensing:

The statistics of the transmitted signals in many communication systems are periodic because of inherent periodicities such as modulation rate and carrier frequency. Generally, cyclostationary features result from the periodicity in the signal or in its statistics like mean and autocorrelation [115]. They can be intentionally induced to assist spectrum sensing. From cyclostationary features [38, 116], a detector can distinguish cyclostationary signals from stationary noise. This is because the noise is wide-sense stationary with no correlation while modulated signals are cyclostationary with spectral correlation due to the redundancy of signal periodicities.

Cyclostationary detectors can differentiate noise from PU signals and have better detection robustness in the low SNR regime. Different to cyclostationary detectors, energy detectors cannot detect weak signals and can cause a high false alarm probability due to noise uncertainty.

3.1.3 Matched Filtering:

From a signal processing point of view, a matched filter correlates a known signal (PU signal), or template, with an unknown received signal to detect the presence of the PU [117]. Matched filtering requires perfect knowledge of the PU signal, such as the operating frequency, bandwidth, modulation type and order, pulse shape, and packet format. One of the important advantage of matched filtering is the short time required to achieve a certain probability of detection. Matched filtering is more robust to noise uncertainty and presents a better detection in the low SNR regime than feature detectors. Moreover, it requires less signal samples to achieve good detection. However, the matched filtering has some disadvantages such as complex implementation and high power consumption [118]. In addition, matched filtering requires precise prior information about certain waveform patterns of PU signals. Otherwise, if such information is wrongly provided, the sensing performance degrades rapidly.

3.1.4 Comparison of different Non-Cooperative Spectrum Techniques:

Performance of the three spectrum sensing techniques –matched filter, energy detector (ED) and cyclostationary detection is compared in this section. Comparison is done on the basis of four parameters. (i) Sensing time, (ii) Cost, (iii) Prior knowledge of the primary signal and (iv) Complexity of the system.

Although energy detection technique has low cost, complexity and sensing time but it also has low accuracy and performance. Matched filter detection gives good accuracy and performance but it has high cost and complexity along with perfect knowledge of primary signal is also required. Cyclostationary analysis has better accuracy and performance and has more cost and complexity but it require only partial knowledge of primary signal, which makes it better technique then matched filter detection. Comparison is presented in the Figure 3.3

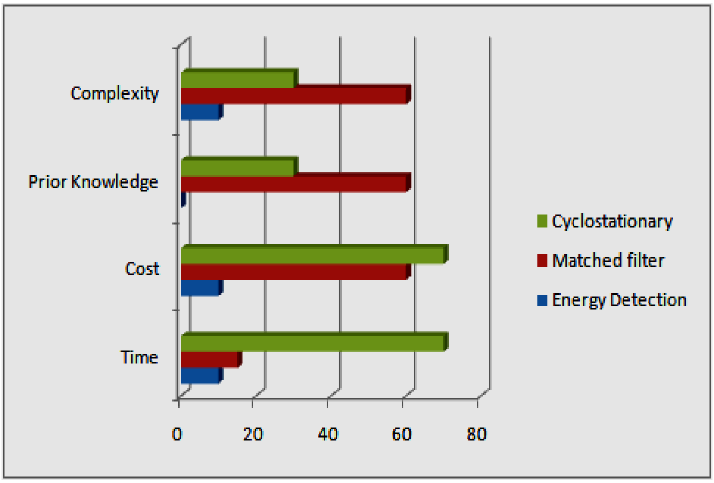

Figure 3.3 Comparison of Different spectrum techniques [119].

Although the performance of Cyclostationary detection method is best among three detection methods but if PU prior knowledge is not known and if design model needs to be simple then ED is best among three detection methods. So for local sensing ED is used in the investigation.

3.2 Cooperative Spectrum Sensing (CSS):

Consider the scenario illustrated in Figure 3.4, where there is a primary system and CR system, both composed by a transmitter and receiver. The SU3 transmitter is not able to detect the transmission of the primary transmitter, because of deep fade or may be because it is outside the incumbent transmission range, i.e., the SNR is below the CR transmitter detection threshold. So the CR transmitter sees the channel as vacant and therefore decides to transmit on it, causing interference to the incumbent receiver. This is known as the hidden node problem. So even if a transmission is not detected by the sensing node, it does not mean that there is not one there, namely because the sensing node may be under a deep fade, due to an obstacle in the terrain.

To overcome these limitations, [120, 121] has proposed the use of cooperation in the spectrum sensing (SS). Since the signal strength varies with the local detector location, the worst fading conditions can be avoided if multiple sensors in different spatial locations share their sensing measurements, i.e., take advantage of the spatial diversity, therefore improving the overall detection performance. The main idea behind the CSS is to enhance the detection performance by exploiting the spatial diversity in the observations of spatially located CRN nodes. Through this cooperation, the CRN nodes can share their individual sensing information and then combine them to achieve a more accurate decision than the ones possible when only the invidual sensing information is available.

From the wireless receiver perspective, the multipath fading and shadowing make the SNR of the received incumbent signal to be small, beyond the capabilities of the receiver to detect, since it might be below the receiver sensitivity. The receiver sensitivity is the capability of the receiver to detect weak signals, and higher is the sensitivity the higher is the hardware complexity and therefore associated cost. Also below a certain SNR threshold, it is not possible to detect the signal, even by increasing the receiver sensitivity, since there is a limit caused by the noise uncertainty, known as the SNR wall. Through the use of cooperation it is possible to relieve the receiver sensitivity requirements and ensure that it is above the SNR wall and make it approximately set to the same level as the nominal path loss, being this called the potential cooperative gain.

The use of CSS schemes also brings drawbacks to the CRN, known as cooperation overhead. This overhead refers to any extra effort that the CRN node needs to do to accomplish CSS when compared to the case where no CSS is done. This extra effort can be extra sensing time, delay, extra spent energy and other operations devoted to accomplish the CSS. Also any performance degradation due to imperfect CR node selection, where the nodes are under correlated shadowing, or vulnerability to security attacks

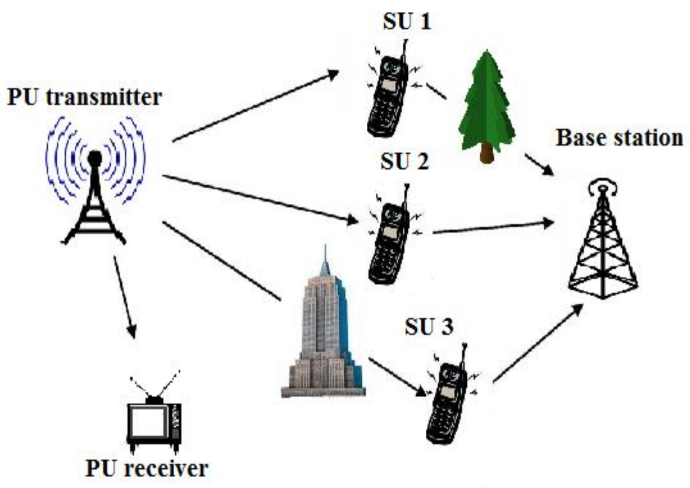

Figure 3.4 Cooperative Spectrum Sensing Under Shadowing and Multi Path Fading [91]

In CSS, all SUs identify the availability of the vacant spectrum independently. Let number of SUs in the network are 'N'. Each SU makes a binary decision based on its local observation and then forwards one bit of the decision to the common base station. Let $D_j \in \{0, 1\}$ denote the local spectrum sensing result of the j^{th} CR. Where {0} indicates that, the SU infers the absence of the PU and {1} infers the presence of the PU. At the common base station, all 1-bit decisions are fused together according to the following logic rule

$$Y = \sum_{j=1}^{k} D_j \ . \tag{3.7}$$

When base station uses k out of N fusion rule, the overall detection and false alarm probabilities are given by [122]

$$Q_f = \sum_{i=k}^{N} \binom{N}{i} {P_f}^i \left(1 - P_f\right)^{N-i}, \tag{3.8}$$

$$Q_d = \sum_{i=k}^{N} \binom{N}{i} {P_d}^i \left(1 - P_d\right)^{N-i}, \tag{3.9}$$

OR rule corresponds to the case when k = 1 and the AND rule corresponds to the case of when k = N. For the OR rule, the base station infers the presence of the PU signal when there exists at least one CR that has the local decision H_1. It can be seen that the OR rule is very conservative for the SUs to use the licensed spectrum. For the AND fusion rule base station infers the presence of the PU signal when all the CRs has the local decision H_1. If k is greater then $\frac{N}{2}$ it is a majority fusion rule.

3.3 Cooperative Spectrum Sensing under Imperfect Reporting:

In practice, channels between the SUs and the base station will also experience fading and shadowing and the performance of CSS will be degraded by the imperfect reporting channels. Let $P_e^{(j)}$ is the error probability of signal transmission over channels between the j^{th} SU and the base station. Then, the CSS performance can be given by [122].

$$Q_f = 1 - \prod_{j=1}^{k}\left[\left(1 - P_f^{(j)}\right)\left(1 - P_e^{(j)}\right) + \left(P_f^{(j)} P_e^{(j)}\right)\right], \tag{3.10}$$

$$Q_m = \prod_{j=1}^{k}\left[P_m^{(j)}\left(1 - P_e^{(j)}\right) + \left(1 - P_m^{(j)}\right)\left(P_e^{(j)}\right)\right], \tag{3.11}$$

where Q_f and Q_m are global probability of false alarm and global probability of miss detection respectively and $P_f^{(j)}$ and $P_m^{(j)}$ are local probability of false alarm and local probability of miss detection for j^{th} user respectively.

3.4 Diversity Combine Techniques

Diversity techniques can be used to improve system performance in fading channels. Instead of transmitting and receiving the desired signal through one channel, ‘V’ copies of the desired signal through ‘Y’ different channels is obtained. The idea is that while some copies may undergo deep fades, others may not. There are different kinds of diversity combining techniques, which are commonly employed in wireless communication systems:

3.4.1 Square Law Selection Diversity Scheme (SLS):

In SLS diversity, the base station only selects the branch with the largest energy, such that $Z_{sls} = \max(Z_1, Z_2, \cdots, Z_V)$. In the case of AWGN channels, the probabilities of false alarm (P_f) and detection (P_d) under a SLS diversity scheme is given by [123]:

$$P_f^{sls} = 1 - \left(1 - \frac{\Gamma\left(u, \frac{\lambda}{2}\right)}{\Gamma(u)}\right)^V \tag{3.12}$$

$$P_d^{sls} = 1 - \prod_{j=1}^{V}\left(1 - Q_u\left(\sqrt{2z_j}, \sqrt{\lambda}\right)\right). \tag{3.13}$$

When there exists fading over 'V' identical independent distributed (i.i.d.), channels, the average probability of detection can be evaluated by averaging ${P_d}^{sls}$ in (3.13) over all possible SNRs as

$$\bar{P}_d{}^{sls} = \int_0^\infty {P_d}^{sls}(y_i, \lambda) f(y_i) dy \quad y_i > 0, \tag{3.14}$$

where $f(y_i)$ is given by

$$f(y_i) = \frac{{y_i}^{V-1} e^{\frac{y_i}{\bar{\Upsilon}_i}}}{(V-1)!\, {\bar{\Upsilon}_i}^{V}}. \tag{3.15}$$

Substituting equation (3.13) and (3.15) in to equation (3.14), the expression for the average probability of detection is obtained. Since the channel are i.i.d., the average probability of detection can be calculated by

$$\bar{P}_d{}^{sls} = 1 - \prod_{i=1}^{V} (1 - P_d(\bar{\Upsilon}_i, u)). \tag{3.16}$$

3.4.2 Square Law Combine (SLC):

Using the SLC scheme, the squared and integrated energy vectors, $X_1, X_2, X_3, \ldots X_k$, from k distributed CRs are gathered at a Fusion center (FC), where the test statistic, $X_{slc} = \sum_{i=1}^{k} X_i$ is formed [123]. Thus, under the H_0 hypothesis in (3.17), if these k fading channels are i.i.d., and all branches have the same noise variance, the test statistic, X_{slc}, follows a central chi-square distribution with a 2ku degree of freedom (DoF). On the other hand, under the H_1 hypothesis, it follows a non-central chi-square distribution with a 2ku DoF and non-central parameter of γ_{slc} as,

$$X_{slc} \sim \begin{cases} {Y^2}_{2ku}, & H_0 \\ {Y^2}_{2ku}(2\gamma_{slc}), & H_1 \end{cases}, \tag{3.17}$$

where $\gamma_{slc} = \sum_{i=1}^{k} \gamma_i$, and γ_i is the SNR in CR node *i*.

In the case of non-fading AWGN channels, the probabilities of false alarm and detection under the SLC diversity reception scheme can be obtained by substituting the DoF to (3.4) and (3.5) as,

$${P_f}^{slc} = \frac{\Gamma\left(ku, \frac{\lambda}{2}\right)}{\Gamma(ku)} \tag{3.18}$$

$${P_d}^{slc} = Q_{ku}\left(\sqrt{2\gamma_{slc}}, \sqrt{\lambda}\right). \tag{3.19}$$

3.4.3 Transmit Diversity:

CSS performance is limited by the probability of error P_e of reporting channel which is due to noisy reporting channels. Transmit diversity can be applied to improve the performance of CSS by reducing P_e. It is based on grouping several nodes (SUs) each with only one antenna. They will make a cluster to form a virtual antenna array. Signal is then transmitted to base station by using Space time block coding (STBC). In this user cooperation the decisions to the base station are reported either directly using TDMA (Time Division Multiple Access) or using transmit diversity in ST coding. If e represent error rate of transmission between interuser channels and ${Q_e}^D$ is error rate due to direct transmission using TDMA and ${Q_e}^S$ is error rate of BPSK (Binary Phase Shift Keying) signal using ST block coding than error rate of reporting channel for transmit diversity is given by [122].

$$P_e = \alpha {Q_e}^S + (1-\alpha){Q_e}^D, \tag{3.20}$$

where $\alpha = (1-\mathrm{e})^2$ denotes the probability of the CRs correctly decoding the received signal coming from each other.

Error rate of BPSK signal using ST block coding given by [122].

$$ {Q_e}^S = \frac{1}{2}\left[1 - \mu \sum_{n=0}^{M-1} \binom{2n}{m} \left(\frac{1-\mu^2}{4}\right)^m\right], \tag{3.21}$$

where $\mu = \sqrt{\frac{(\bar{\Upsilon}/R)}{1+(\bar{\Upsilon}/R)}}$, R = no. of cooperative antennas, $\bar{\Upsilon}$ = average SNR of the reporting channel and m =Nakagami fading parameter. For Rayleigh fading distribution m=1.

3.5 Results and discussion

The receiver operating characteristics (ROC) plots or complimentary ROC plots can give good estimation of the network. ROC is a probability curve. It tells how much model is capable of distinguishing between classes. In spectrum sensing, P_d vs. P_f curve is known as ROC curve and P_m (1-P_d) vs. P_f curve is known as complimentary ROC curve. In this section performance of non-cooperative and CSS is plotted in terms of complimentary

ROC plots. The simulation parameters taken as, total number of CR users (N) = 4, time bandwidth product (u) = 5 and average SNR over Rayleigh fading (Ύ) = 10 dB.

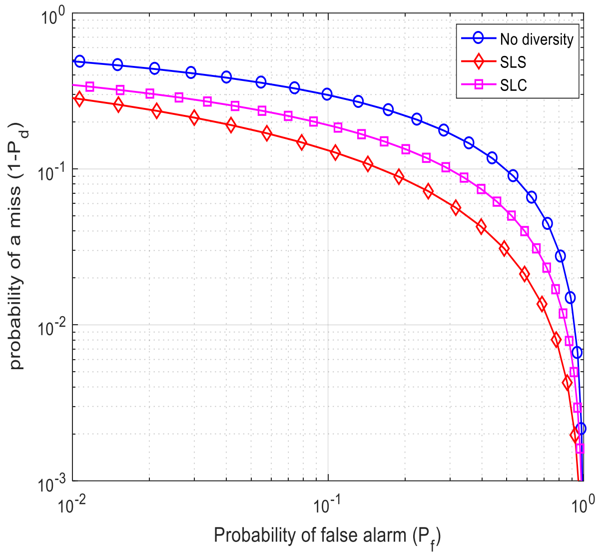

Figure 3.5 Complimentary ROC plot of non-cooperative spectrum sensing with and without diversity

Figure 3.5 show complimentary ROC plot for non-cooperative spectrum sensing without diversity and with SLC and SLS diversity combining techniques. The plot shows that diversity combining techniques can improve the performance of non-cooperative spectrum sensing.

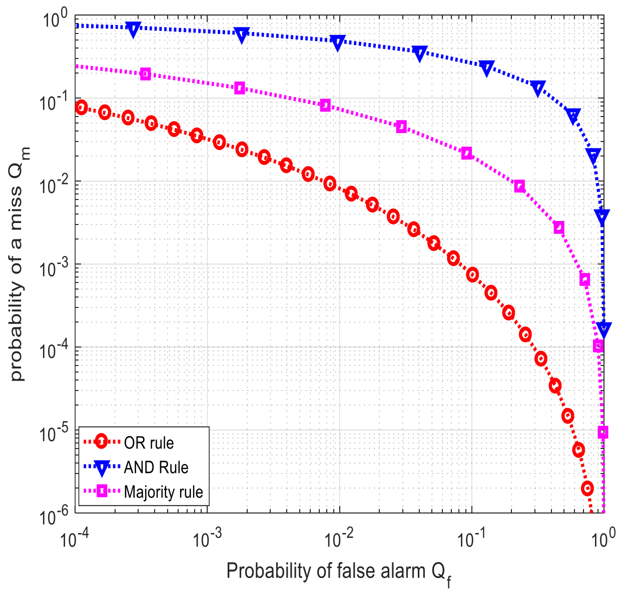

Figure 3.6 Complimentary ROC curve for AND, OR and Majority rule

Results published in the paper: "Performance improvement of CSS over imperfect reporting using diversity reception in cognitive radio networks." World Journal of Engineering (2019).DOI: 10.1108/WJE-09-2017-0288

It can be observed in Figure 3.5 that probability of miss decreases when diversity combining techniques are used. It is also observed that SLS performs better than SLC diversity combining technique. It is because in SLS technique the signal with highest SNR is selected. Quantitatively at P_f = 0.1, P_m = 0.29, 0.19, 0.13 for no diversity, with SLC and with SLS diversity respectively.

Figure 3.6. show complimentary ROC plot of CSS with different fusion conditions. It is observed from Figure 3.6 that detection probability is maximum for OR fusion and minimum for AND fusion because for OR fusion if single CR user sends information of PU presence then fusion center (FC) consider it to be present on the other hand in AND fusion, FC will not consider PU presence until all CR users sends information of PU presence. We shall consider the OR rule for further study.

In Figure 3.7 detection probability is plotted against average SNR for fixed false alarm probability (P_f) = 0.01. Figure 3.7 also show similar trend as in Figure 3.6, detection probability is maximum for OR fusion and minimum for AND fusion.

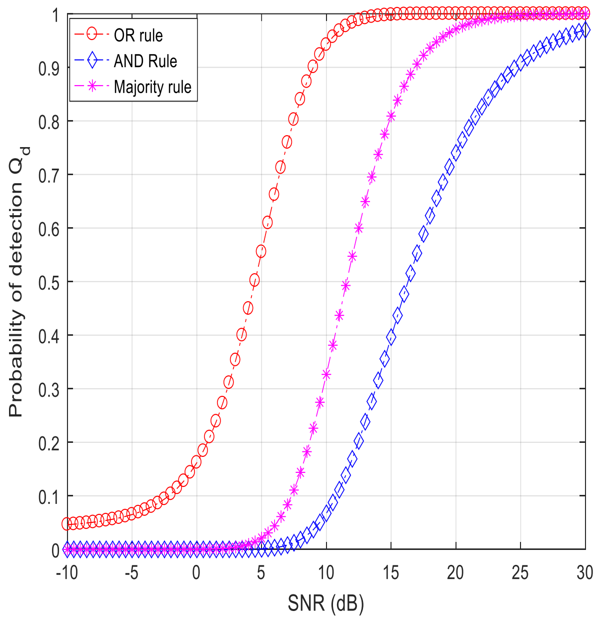

Figure 3.7 Detection probability vs. SNR plot for AND, OR and Majority rule

It is also observed from Figure 3.7 that as the value of SNR increases, detection probability increases because detection of PU signal is easy in better radio conditions. Figure 3.8 show Complimentary ROC curve of CSS with OR fusion over imperfect reporting channel at different SNR. For figure 3.8 error probability (P_e) of imperfect reporting is taken as 0.001.

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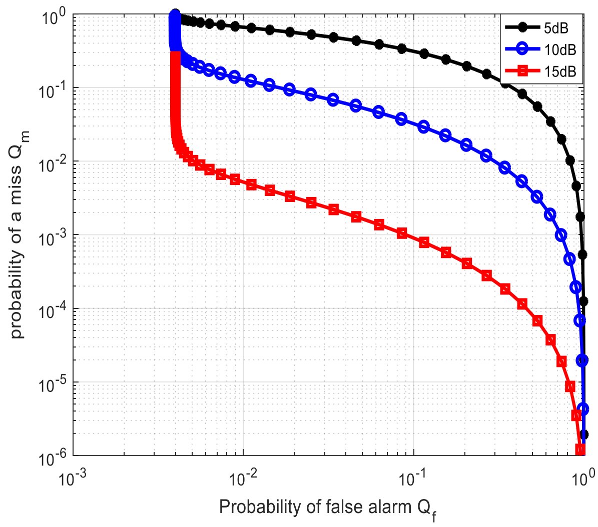

Figure 3.8 Complimentary ROC curve of CSS for imperfect reporting at different SNR

It is observed from Figure 3.8 that due to imperfect reporting channel false alarm probability (Q_f) is limited by a lower bound and bound does not depend on the channel SNR. Before this lower bound value of Q_f detection of PU is not possible. In Figure 3.8 the lower bound Q_f is 0.004.

Figure 3.9 show Complimentary ROC curve of CSS with OR fusion over imperfect reporting channel when number of CR users increases from 1 to 4. Error probability (P_e) of imperfect reporting is taken as 0.001.

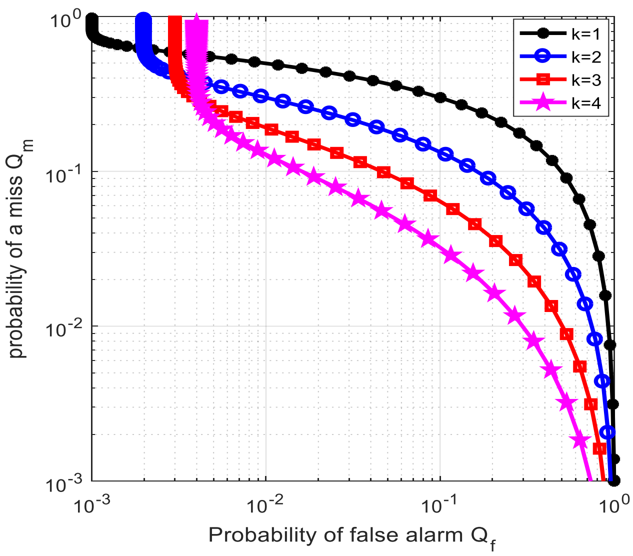

Figure 3.9 Complimentary ROC curve of CSS for imperfect reporting for different number of CR users

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It is observed from Figure 3.9 that due to imperfect reporting channel false alarm probability (Q_f) is limited by a lower bound and bound increases as number of CR user increases.

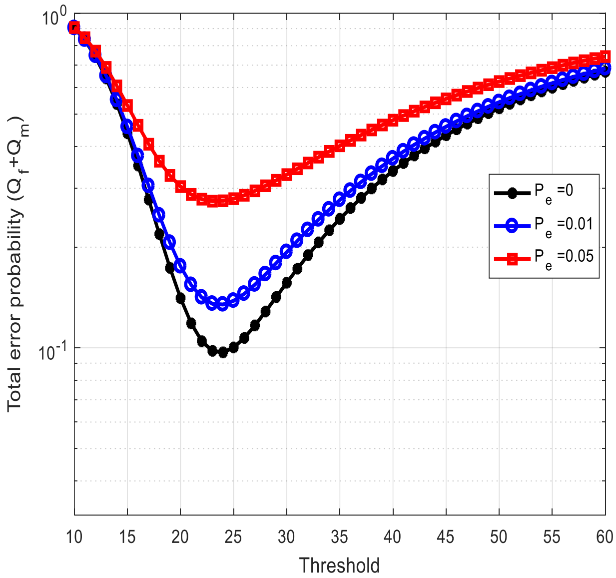

Figure 3.10 Total probability Vs. threshold curve for different error probabilities

In Figure 3.10, total error probability (Q_f +Q_m) is plotted against detector threshold value at different error probability (P_e) of reporting channel. Figure 3.10 show the effect of imperfect reporting on the performance of CSS as it is clear from the Figure 3.10 as the value of error probability of reporting channel increases, Total error probability of CSS decreases.

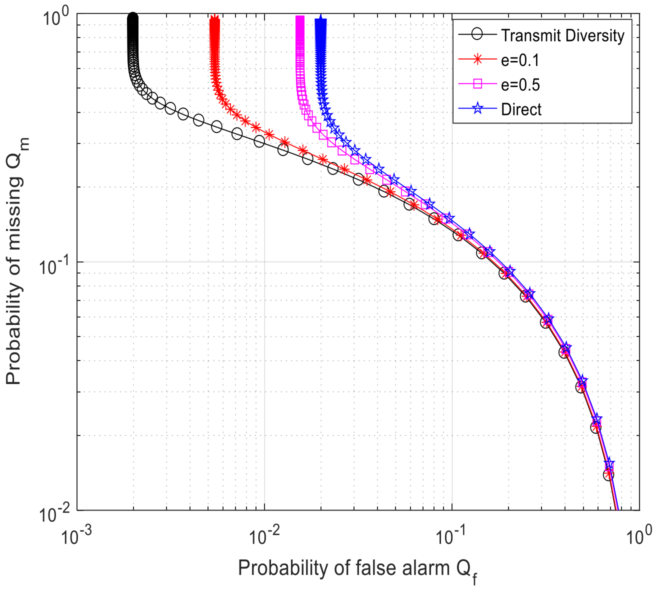

Figure 3.11 Complimentary ROC plot of CSS using transmit diversity technique

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Figure 3.11 show complimentary ROC plot of CSS with OR fusion using transmit diversity described in section 3.5.3. It can be observed from Figure 3.8 that lower bound in Q_f decreases as the value of error probability decreases and it is lowest when transmit diversity is employed. In Figure 3.11 this lower bound Q_f is 0.02 when transmit diversity is not applied and lower bound Q_f is 0.002 when transmit diversity is used. It is also observed that transmit diversity can decrease the value of lower bound Q_f but it cannot increase the value of detection probability. Hence transmit diversity is used along with Square law selection (SLS) receive diversity to enhance the performance of CSS in imperfect reporting scenario.

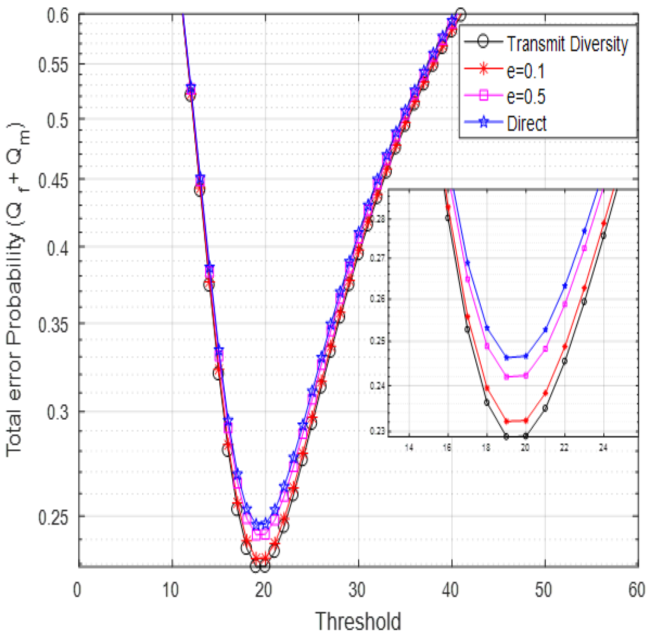

Figure 3.12 Total probability vs. threshold curve with transmit diversity

In Figure 3.12 total error probability is plotted against threshold with transmit diversity. It can be observed form Figure 3.12 that total error probability decreases when transmit diversity employed because due to transmit diversity lower bound of Q_f decreases and because of that miss detection also decreases beyond lower bound Q_f. For direct transmission total error probability is 0.246 and it is decreased to 0.228 when transmit diversity is applied.

Figure 3.13 show complimentary ROC plot of CSS with No diversity, SLS diversity and transmit diversity. For No diversity case, lower bound Q_f is 0.004 after applying SLS diversity detection probability is improved but lower bound Q_f is also increased to 0.008 so we apply transmit diversity with SLS diversity to improve the lower bound Q_f to 0.0008.

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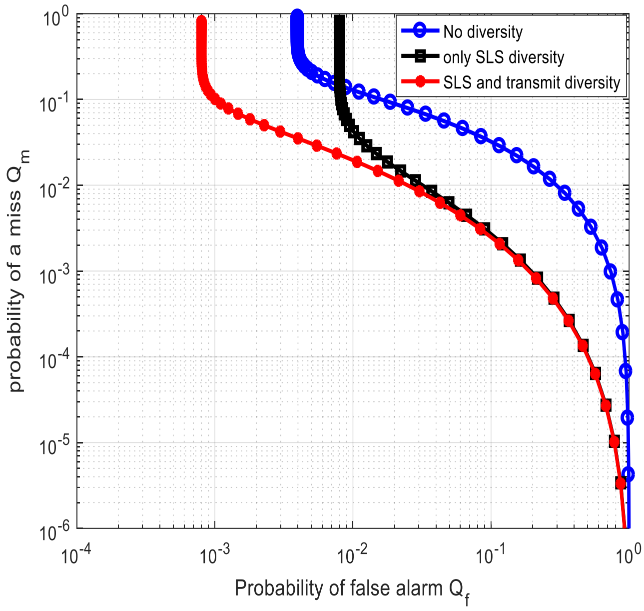

Figure 3.13 Performance comparison (Q_m versus Q_f) of CSS with No diversity and with SLS and transmit diversity

Thus at O_f = 0.01 detection probability increases up to 11.55% when SLS diversity is applied and lower bound Q_f decrease up to 80% when transmit diversity is applied.

3.6 Discussion

The results in Figure 3.6 and 3.7 show the performance of CSS for different fusion rules and SNR. It is found that detection performance is better for OR fusion and hence OR fusion is used for the further discussion. The CSS with more CR users has better performance. However, when false alarm (Q_f) decreases to a threshold, lower bound Q_f, missed detection probability will drastically increase to one and hence detection probability will decrease to zero. Moreover, lower bound Q_f does not depend on channel SNR as observed from Figure 3.8 but it depends upon number of CR users as shown in Figure 3.9. False alarm probability is the probability of event that FC infers the presence of the PU while in fact the PU signal is not transmitted. Thus, due to false alarm the licensed frequency band is vacant but not utilized. Therefore, false alarm can be interpreted as bandwidth efficiency loss. From Figure 3.11 it is evident that bandwidth efficiency loss decreases if transmit diversity is used.

Transmit diversity can decrease the bandwidth efficiency loss but it cannot increase detection probability. Hence transmit diversity is used along with Square law selection (SLS) receive diversity to enhance the performance of CSS in heavy shadowing scenario. The curve in Figure

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3.13 show both lower bound Q_f and that high detection probability can be achieved. This is because SLS diversity allows us to achieve maximum detection probability and transmit diversity results in lowering the bound of Q_f.

Table 3:1 Comparison with previous work

Work	**Diversity**	**Average SNR**	**lower bound Q_f**	**Miss detection at $Q_f = 0.02$**
[122]	Relay with transmit	15 dB	0.002	0.07
Proposed	SLS with transmit	10 dB	0.0008	0.09

Table 3.1 compares the result of Figure 3.13 with previous similar work in [122].

3.7 Conclusion

In this chapter, both non-cooperative and CSS performance is discussed. Performance of non-cooperative spectrum sensing can be improved by employing diversity combining techniques. The performance of non-cooperative spectrum sensing is affected by hidden terminal. To solve this problem CSS is used. CSS performance is limited by noisy reporting channel which can be shown by introducing probability of reporting error. The lower bound of probability of false alarm linearly increases with the probability of reporting error. To solve this problem a transmit diversity based CSS method is proposed. It uses space-time coding and space frequency coding by viewing SU as distributed antenna arrays. Further Square law selection (SLS) diversity technique is proposed with CSS to improve the performance of detection. It is observed that detection probability increases up to 11.55% when SLS diversity is applied and lower bound Q_f decrease up to 80% when transmit diversity is applied.

In next chapter, performance of CSS is investigated over different radio environmental conditions other than Rayleigh fading and also clustering is introduced in CSS to further improve the performance.

CHAPTER 4: CLUSTER BASED CSS IN CRN OVER FADING CHANNELS

A non-cooperative spectrum sensing faces the problem of shadowing and hidden terminal due to which the CR user fails to monitor the vacant spectrum. To solve the problem of hidden terminal and shadowing in non-cooperative spectrum sensing, CSS is used. CSS can be divided in two categories, centralised and distributed. In this chapter comparison of centralised and distributed CSS is presented and a cluster based distributed CSS is proposed over fading channel with different fusion rules and effect of number of CR users and number of clusters on the performance has been investigated. An analytical framework has been presented to evaluate different parameters related to spectrum sensing i.e. detection probability, false alarm probability and missed detection probability over Rayleigh, Rician and Nakagami fading channel. Based on developed framework, performance of cluster based distributed CSS has been compared with the centralised CSS. Further performance improvement is achieved by using Square law selection (SLS) and Maximum ratio combining (MRC) diversity schemes.

4.1 System Model for Cluster based CSS

4.1.1 Centralised Cooperative Spectrum Sensing:

If there are 'N' number of CR users and single PU with a common fusion centre (FC) as in Figure 4.1. Each SU detects the presence of PU using energy detector (ED).

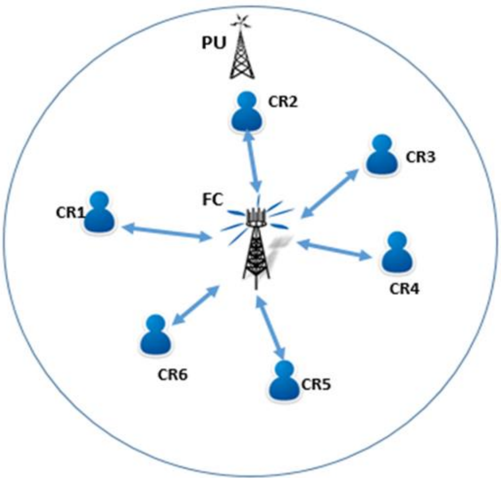

Figure 4.1 Centralised CSS

In an energy detector signal x(t) is given as input and it gives an output which is in the form of binary decision with reference to presence of PU. For jth CR in the network. There are following two hypotheses:

$$Z_j(t) \triangleq \begin{cases} w_j(t), & H_0 \\ h_j x(t) + w_j(t) & H_1, \end{cases} \tag{4.1}$$

where $Z_j(t)$ is the signal received at the j^{th} CR, $x(t)$ is the transmitted signal from the PU, $w_j(t)$ is the gaussian noise, and h_j is the complex gain of the channel. Based on the system model in (4.1), we can calculate $\|E_j\|$, i.e., the computed energy received, the Signal-to-Noise Ratio (SNR) at the CR, i.e., Υ_j, and the time bandwidth product $\bar{u}$. The PU signal is detected by comparing the energy $\|E_j\|$ with a threshold value λ_j. Therefore, the false alarm probability is given by $P_f^{(j)}$ = Prob $\{\|E_j\| > \lambda_j|H_0\}$ and the detection probability is given by $P_d^{(j)}$ = Prob $\{\|E_j\| > \lambda_j|H_1\}$. Based on the hypothesis in (4.1), according to [123], the false alarm probability, the detection probability and the miss detection probability for additive white gaussian noise (AWGN) channel, are given by

$$P_f^{(j)} = Pr\left[\, y_j > \lambda j|H_0\right] = \frac{\Gamma\left(\bar{u}, \frac{\lambda j}{2}\right)}{\Gamma(u)} \tag{4.2}$$

$$P_d^{(j)} = Pr\left[\, y_j > \lambda j|H_1\right] = Q_{\bar{u}}\left(\sqrt{2\Upsilon}, \sqrt{\lambda}\right) \tag{4.3}$$

$$P_m^{(j)} = 1 - P_d^{(j)}. \tag{4.4}$$

Average probability of detection under fading scenario can be calculated by averaging Equation (4.3) i.e.

$$\tilde{P}_d = \int_0^\infty Q_{\bar{u}}\left(\sqrt{2\mathrm{x}}, \sqrt{\lambda}\right) f_\Upsilon(x)dx, \tag{4.5}$$

where $f_\Upsilon(x)$ is the probability density function (PDF) of Υ under fading.

In centralised CSS, all CR users detect the availability of the vacant spectrum individually. After performing local spectrum sensing each SU makes a binary decision and then forward decision to the fusion centre. Let $S_j \in [\![0,1]\!]$ denote the independent local sensing result of the j^{th} CR. Where $[\![0]\!]$ indicates presence of vacant spectrum and $[\![1]\!]$ indicates the absence of the vacant spectrum. At the fusion centre, decisions are fused together according to the following logic rule

$$Y = \sum_{j=1}^{N} S_j \begin{cases} \geq k, & H_1 \\ < k & H_0, \end{cases} \tag{4.6}$$

Here k = 1 corresponds to OR rule and k = N corresponds to AND rule. Based on (4.6), False alarm and miss detection probability of centralised CSS for OR and for AND rule is given by

$$Q_f^{\,or} = 1 - \prod_{j=1}^{N}\left(1 - P_f^{\,(j)}\right) \tag{4.7}$$

$$Q_m^{\,or} = \prod_{j=1}^{N} P_m^{\,(j)} \tag{4.8}$$

$$Q_f^{\,and} = \prod_{j=1}^{N}\left(P_f^{\,(j)}\right) \tag{4.9}$$

$$Q_d^{\,and} = \prod_{j=1}^{N} P_d^{\,(j)} \tag{4.10}$$

$$Q_m^{\,and} = 1 - Q_d^{\,and}, \tag{4.11}$$

where $P_f^{\,(j)}$ denotes the probability of false alarm and $P_m^{\,(j)}$ denotes the probability of miss detection of the j^{th} CR user given in equations (4.2) and (4.3) respectively. If P_e is the bit error rate between SU and FC and a common threshold is used for all CR users then $P_f^{\,(j)} = P_f$ and $P_d^{\,(j)} = P_d$. False alarm and detection probability for this imperfect reporting can be determined by

$$P_{f1} = P_f(1 - P_e) + \left(1 - P_f\right)P_e \tag{4.12}$$

$$P_{d1} = P_d(1 - P_e) + (1 - P_d)P_e. \tag{4.13}$$

4.1.2 Distributed CSS:

Unlike centralised CSS, there is no common base station in distributed CSS. Each SU performs the nearby local sensing. The information of local sensing exchanges between the other SUs. Collective probability of presence or absence of PU is finally decided by SUs. Each CR then make a final decision based on the information it receives from the other users. In Figure 4.2 a distributed CSS with six CR users and one PU is illustrated.

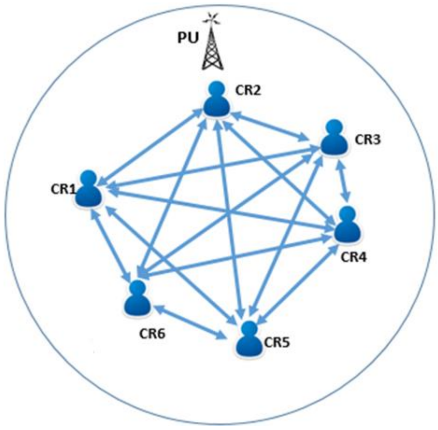

Figure 4.2 Distributed CSS

4.2 Cluster based distributed CSS

In cluster-based distributed CSS each SU performs the local spectrum sensing. The sensing information of local spectrum sensing is exchange between the other SUs of same cluster by a fusion rule. This fusion takes place at cluster head (CH) as shown in Figure 4.3.

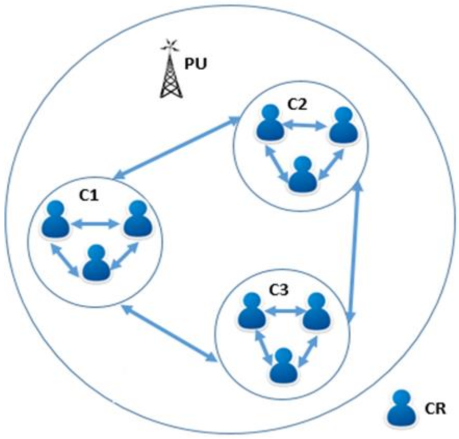

Figure 4.3 Cluster based distributed CSS

In each cluster, SUs appoints a CH. CH can be selected by SUs randomly or based on some criterion. An ideal CH has high residual energy, maximum number of neighbouring nodes and lowest distance from base station. It is difficult to find all the criterion simultaneously in single node. So, the CH is selected by multiple attribute decision-making approaches like - low energy adaptive cluster hierarchy (LEACH), Distributed hierarchical agglomerative clustering (DHAC), Hybrid energy-efficient distributed protocol (HEED) etc. [124].

The clustering algorithms can be classified in three categories: (i) centralized clustering, (ii) distributed clustering and (iii) hybrid clustering. In centralized clustering, cluster head is fixed but in distributed clustering, cluster head is not fixed. The CH location changes from node to node. In hybrid clustering features of both centralised and distributed clustering is included. In this section centralised clustering approach is used in which CH is fixed.

CH is responsible for network management, information circulation and data collocation. Non-CH are responsible for local sensing. Now CHs of different clusters exchange information between each other by same or other fusion rule to finally decide the presence or absence of PU. In centralised CSS without clustering, the channel between PU and SUs (sensing channel) is assumed ideal i.e. without any noise and the channel between SUs and the fusion center (reporting channel) is considered noisy with error probability (P_e). For cluster based CSS, the sensing channel between PU and SUs is considered ideal but the reporting channel between SUs and cluster heads (CHs) and channel between CH and CH is considered noisy with same error probability (P_e). For the proposed cluster based CSS, there are four fusion possible:

4.2.1 OR-OR Fusion

Each individual SU detect the empty spectrum by local sensing in a cluster. This sensing information is fused at CH by OR fusion. Subsequently each CH fuse the sensing information with other CHs in OR fusion. In Figure 4.3, SUs in the cluster exchange information and fuse at CH using OR fusion and CHs of C_1, C_2, C_3 also fuse its information with OR fusion.

The probability of false alarm and miss detection of distributed CSS for OR-OR rule is derived from centralised CSS and is given as:-

$$Q_f{}^{or-or} = 1 - \prod_{j=1}^{l} \left(1 - Q_f{}^{or(j)}\right) \tag{4.14}$$

$$Q_m{}^{or-or} = \prod_{j=1}^{l} Q_m{}^{or(j)} \,, \tag{4.15}$$

where j is the number of CR users in a Cluster and l is the total no of clusters.

4.2.2 OR-AND Fusion

The CR users will exchange information using OR fusion and clusters will share their decision with AND fusion. The false alarm and detection probabilities of distributed CSS for OR-AND rule derived from centralised CSS and is given as:-

$$Q_f{}^{or-and} = \prod_{j=1}^{l} \left(Q_f{}^{or(j)}\right) \tag{4.16}$$

$$Q_d{}^{or-and} = \prod_{j=1}^{l} Q_d{}^{or(j)} \,. \tag{4.17}$$

4.2.3 AND-OR Fusion

The CR users will exchange information using AND fusion and clusters will share their decision with OR fusion. The false alarm and miss detection probability of distributed CSS for AND-OR rule derived from centralised CSS and is given as:-

$$Q_f{}^{and-or} = 1 - \prod_{j=1}^{l} \left(1 - Q_f{}^{and(j)}\right) \tag{4.18}$$

$$Q_m{}^{and-or} = \prod_{j=1}^{l} Q_m{}^{and(j)}. \tag{4.19}$$

4.2.4 AND-AND Fusion

The CR users will exchange information using AND fusion and clusters will also share their decision with AND fusion. False alarm and detection probability of distributed CSS for AND-AND fusion rule derived from centralised CSS and is given as:-

$$Q_f{}^{and-and} = \prod_{j=1}^{l} \left(Q_f{}^{and(j)}\right) \tag{4.20}$$

$$Q_d{}^{and-and} = \prod_{j=1}^{l} Q_d{}^{and(j)} \,. \tag{4.21}$$

4.3 Fading Channel Distributions

In wireless communications, fading is variation of the attenuation of a signal with various variables. A fading channel is a communication channel that experiences fading. Rayleigh, Nakagami and Rician fading channels are useful models of real-world phenomena in wireless communications. Rayleigh distribution is the most used signal model in wireless communications because it represents the worst fading case. Nakagami fading is generalized distribution that can model different fading environments; also, Rayleigh and one-sided Gaussian distribution are special cases of Nakagami-m model. Rician distribution suits better in sub-urban areas where LOS components exist.

4.3.1 Rayleigh Fading Channel

If the received signal amplitude follows the Rayleigh distribution, the SNR (Υ) distribution can be formulated according to [125]:

$$f_{\Upsilon}(\Upsilon) = \frac{1}{\bar{\Upsilon}} \exp\left(-\frac{\Upsilon}{\bar{\Upsilon}}\right) ; \qquad \Upsilon \geq 0, \tag{4.22}$$

where $\overline{\Upsilon}$ is average SNR. We can calculate probability of detection $\bar{P}_{d^{ray}}$ by substituting Equation (4.22) in Equation (4.5), i.e.

$$\bar{P}_{d^{ray}} = \frac{1}{1+\overline{\Upsilon}} \sum_{n=1}^{\bar{u}-1} \left(\frac{\lambda}{2}\right)^{n} \frac{exp\left(-\lambda/2\right)}{n!} \; {}_1F_1\left[1; n+1; \frac{\overline{\Upsilon}\lambda}{2(1+\overline{\Upsilon})}\right] + exp\left[-\frac{\lambda}{2(1+\overline{\Upsilon})}\right], \tag{4.23}$$

where ${}_1F_1$ (.; . ; .) denotes confluent hypergeometric function.

4.3.2 Nakagami Fading Channel

If the received signal amplitude follows the Nakagami distribution, the SNR (Υ) distribution can be formulated according to [125]

$$f_{\Upsilon}(\Upsilon) = \left(\frac{m}{\overline{\Upsilon}}\right) \frac{\Upsilon^{m-1}}{\Gamma(m)} \exp\left(\frac{m\Upsilon}{\overline{\Upsilon}}\right) ; \quad \Upsilon \geq 0, \tag{4.24}$$

where m is a constant known as the fading parameter for Nakagami channel.

We can calculate probability of detection $\bar{P}_{d^{nak}}$ for Nakagami distribution by substituting Equation (4.24) in Equation (4.5), i.e.

$$\begin{aligned}\bar{P}_{d^{nak}} = {} & \left(\frac{m}{m+\overline{\Upsilon}}\right)^{m} \sum_{n=1}^{\bar{u}-1} \left(\frac{\lambda}{2}\right)^{n} \frac{exp\left(-\lambda/2\right)}{n!} {}_1F_1\left[m; n+1; \frac{\overline{\Upsilon}\lambda}{2(m+\overline{\Upsilon})}\right] + \\ & \left(\frac{\overline{\Upsilon}}{m+\overline{\Upsilon}}\right) exp\left[-\frac{\lambda \mathrm{m}}{2(m+\overline{\Upsilon})}\right] \times \left\{\sum_{k=0}^{m-2} \left(\frac{m}{m+\overline{\Upsilon}}\right)^{k} G_k\left[-\frac{\overline{\Upsilon}\lambda}{2(m+\overline{\Upsilon})}\right] + \right. \\ & \left. \left(\frac{m+\overline{\Upsilon}}{\overline{\Upsilon}}\right)\left(\frac{m}{m+\overline{\Upsilon}}\right)^{m-1} G_{m-1}\left[-\frac{\overline{\Upsilon}\lambda}{2(m+\overline{\Upsilon})}\right]\right\},\end{aligned} \tag{4.25}$$

where G_r (.) is the Laguerre polynomial of degree r.

4.3.3 Rician Fading Channel

For Rician distribution the PDF of random variable Υ is given by [125]

$$f_{\Upsilon}(\Upsilon) = \frac{1+q}{\overline{\Upsilon}} \exp\left[-k - \frac{(1+q)\Upsilon}{\overline{\Upsilon}}\right] I_0\left(2\sqrt{\frac{q(1+q)\Upsilon}{\overline{\Upsilon}}}\right) ; \Upsilon \geq 0, \tag{4.26}$$

where q is a constant known as the Rician parameter defined as the ratio of the power in the dominant component to the power in the scattered path and I_n (.) is n^{th} order Bessel function of first kind.

The average probability of detection $\bar{P}_{d^{ric}}$ can be calculated by substituting Equation (4.26) in Equation (4.5), i.e.

$$\bar{P}_{d^{ric}} = \frac{1+q}{\bar{\Upsilon}} \exp(-q) \sum_{n=0}^{\infty} \frac{\Gamma\left(\bar{u}+n, \lambda/_2\right)}{\Gamma(\bar{u}+n)} \left(\frac{\bar{\Upsilon}}{1+q+\bar{\Upsilon}}\right)^{n+1} \times 1F1 \left[n+1; 1; \frac{q(1+q)}{1+q+\bar{\Upsilon}}\right]. \tag{4.27}$$

Rician parameter q = 0, represents Rayleigh distribution.

4.4 Diversity Combining Techniques in CB-CSS

As, it is already discussed in previous chapter that diversity techniques can be used to improve system performance in fading channels. Instead of transmitting and receiving the desired signal through one channel, 'V' copies of the desired signal through 'Y' different channels is obtained. It is observed from the results in previous chapter that performance of SLS diversity is better compared to SLC diversity. In this section, SLS diversity combine technique is used to improve detection probability of CBCSS and a weight based diversity combining technique known as maximum ratio combine is introduced.

4.4.1 Square Law Selection (SLS) Diversity

In SLS diversity, the receiver only receive signal from the branch which has the largest energy, such that $X_{sls} = \max\{X_1, X_2, \cdots, X_V\}$. In case of Nakagami channel, the probabilities of false alarm (P_f) and probability of detection (P_d) under SLS diversity scheme is given by [123]

$$P_f^{\,sls} = 1 - \left(1 - \frac{\Gamma\left(u, \frac{\lambda}{2}\right)}{\Gamma(u)}\right)^V \tag{4.28}$$

$$P_d^{\,sls} = 1 - \prod_{j=1}^{V}\left(1 - \bar{P}_{d^{nak}}\right). \tag{4.29}$$

For V different channels, the probability of detection can be evaluated by averaging $P_d^{\,sls}$ in (4.29) over all possible SNR values.

4.4.2 Maximum Ratio Combining (MRC) Diversity

When the signal is received with MRC diversity reception then received signal $\{z_i(t)\}_{i=1}^{V}$ are weighted and then combined. After combining the new signal is received i.e. $z_{mrc}(t) = \sum_{i=1}^{V} w_i z_i(t)$.

If we define $\left(\frac{m}{m+\bar{\Upsilon}}\right) = \beta$ in equation (4.25) then for Nakagami fading channel, detection probability (P_d) can be determined under MRC diversity by replacing m with mV in equation (4.25) except in β, where V is the number of diversity branch.

4.5 Numerical Results

The performance analysis of spectrum sensing with fusion rules described in Section 4.2 is analyzed assuming the perfect report channels between the fusion centre and SUs. The number of cluster and users within a cluster is equal to two (2), in order to keep the design model simple.

To evaluate the performance, probability of detection is plotted against SNR for centralised and distributed CSS in Figure 4.4 and Figure 4.5. These Figures are plotted for Rayleigh fading channels and Nakagami fading channels (m = 3) respectively for time bandwidth product (u) = 1 and average SNR is varied.

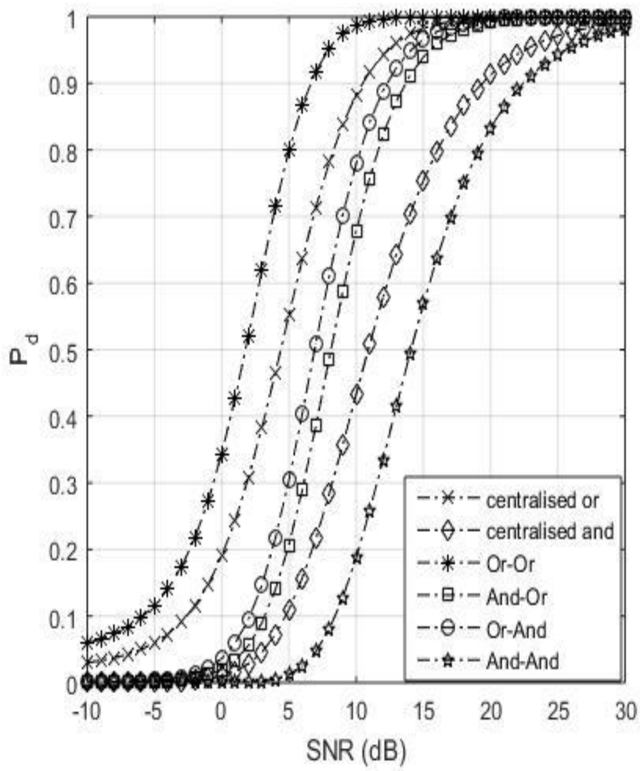

Figure 4.4 Performance of Rayleigh fading channel for different fusion rules

The comparison of centralised and distributed CSS for different values of SNR is reported in Figure 4.4. From Figure 4.4 it can be observed that in distributed OR-OR fusion SNR less than 10dB is required to attain probability of detection of 0.9. Whereas in other fusion schemes SNR more than 10dB is required to attain 0.9 P_d because in OR-OR fusion rule, if at least one SU or one cluster has local decision of PU presence, than FC indicates presence of PU. The performance of OR-OR fusion of CBCSS is better than OR fusion of centralised CSS as user cooperation increases in cluster based approach and hence detection performance increases.

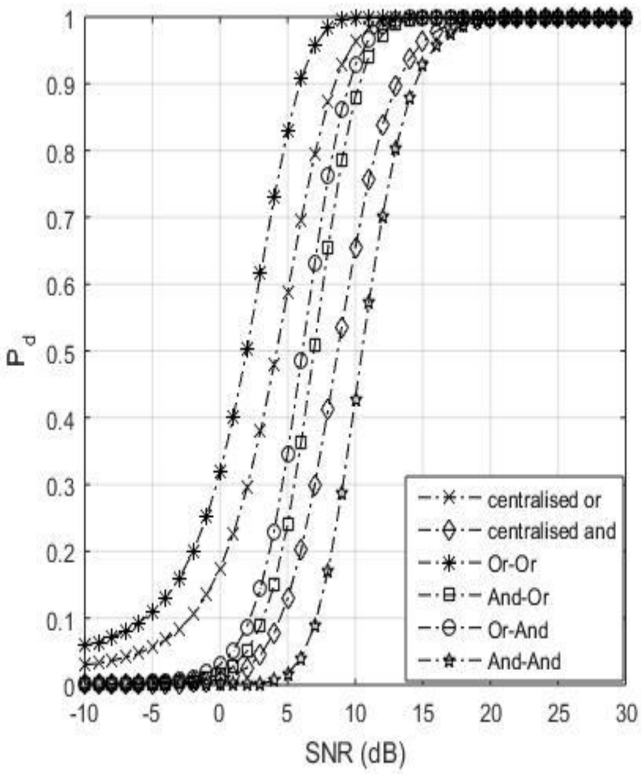

Figure 4.5 Performance of Nakagami fading channel (m=3) for different fusion rules

It can be observed from Figure 4.5 that probability of detection over Nakagami fading channel is greater than Rayleigh fading channel. The slope of the P_d vs. SNR curve is steeper over Nakagami channel compered to Rayleigh channel because for m > 1, the fluctuation of the signal strength reduces compared to Rayleigh fading.

Results published in the paper: “Performance comparison of centralised and distributed CSS over fading channels in cognitive radio” Cogent Engineering Vol. 4, Iss. 1,2017. DOI: 10.1080/23311916.2017.1355599

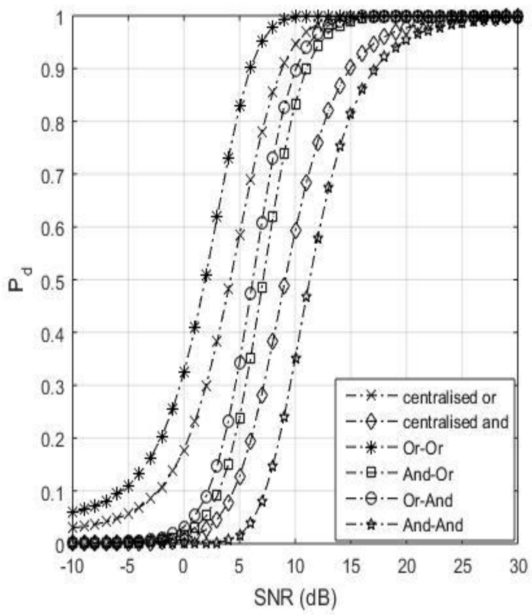

Figure 4.6 Performance of Rician fading channel (q=3) for different fusion rule

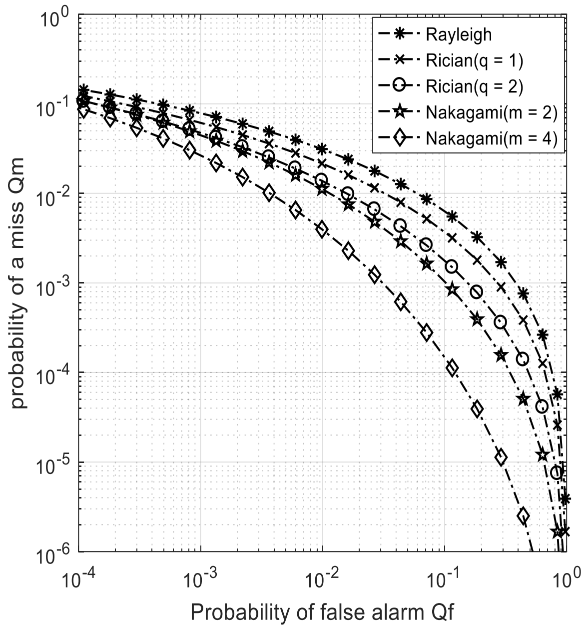

Figure 4.7 Complimentary ROC plot of OR-OR fusion for different fading channel

Figure 4.6 show the P_d vs. SNR plot for Rician Fading distribution for Rician factor q = 3. It is observed from Figure 4.6 that performance over Rician fading is similar to Nakagami fading and is better as compared to Rayleigh fading.

Figure 4.7 illustrates complimentary ROC curves for OR-OR fusion over Nakagami, Rician and Rayleigh fading channels. Rician q = 0 and Nakagami m = 1 curves coincide with Rayleigh

Results published in the paper: "Performance comparison of centralised and distributed CSS over fading channels in cognitive radio" Cogent Engineering Vol. 4, Iss. 1,2017. DOI: 10.1080/23311916.2017.1355599

curve and therefore not shown here. Clearly performance improvement is observed for m, 2 to 4 and q, 1 to 2. The Rician fading constant q is the ratio of power in direct path and scattered paths. Larger values of q gives better performance as we can see in Figure 4.7, performance improves as Rician fading constant increases.

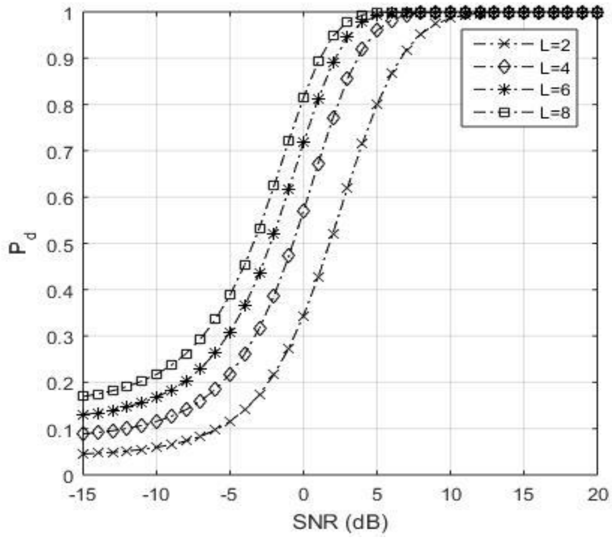

Figure 4.8 Performance of OR-OR fusion for different number of clusters (number of CR user in cluster is 2) L is the number of clusters

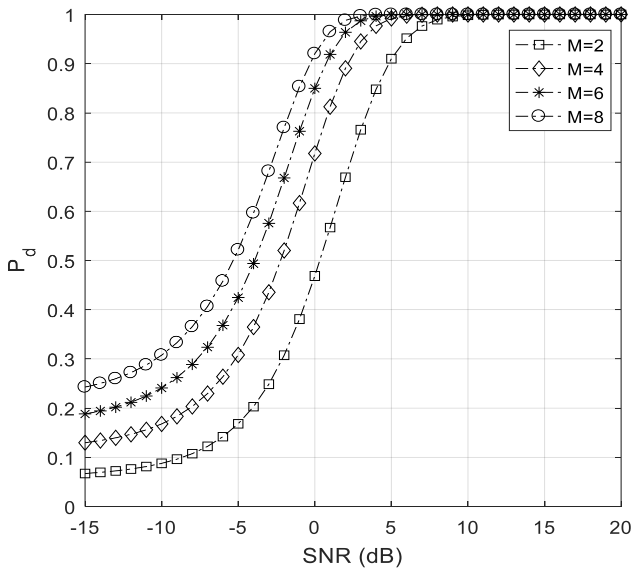

Figure 4.9 Performance of OR-OR fusion for different number CR users in a clusters (number of cluster is 3) M is the number of CR users in a cluster

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Figure 4.8 and Figure 4.9 show P_d vs SNR plot of cooperative CSS with OR-OR fusion over Rayleigh fading channel with different number of CR users in a cluster and different number of clusters. Clearly the greater is the number of clusters or number of SUs in the cluster, the higher performance the network can achieve. In Figure 4.8 total number of CR users in a cluster is 2 and number of clusters are varied. In Figure 4.9 total number of clusters are 3 and number of CR users in a cluster is varied.

Thus it can be observed from Figure 4.8 and Figure 4.9 that probability of detection increases in both the cases as total number of CR users or total number of clusters increases. If number of CR users and number of clusters increases, user cooperation increases and chances of detection of empty spectrum increases. However, with the increase of both L and M, energy consumption and overhead of the network increases. Since detection probability is maximum for OR-OR fusion over Nakagami fading channel, rest results are discussed taking OR-OR fusion over Nakagami channel under consideration.

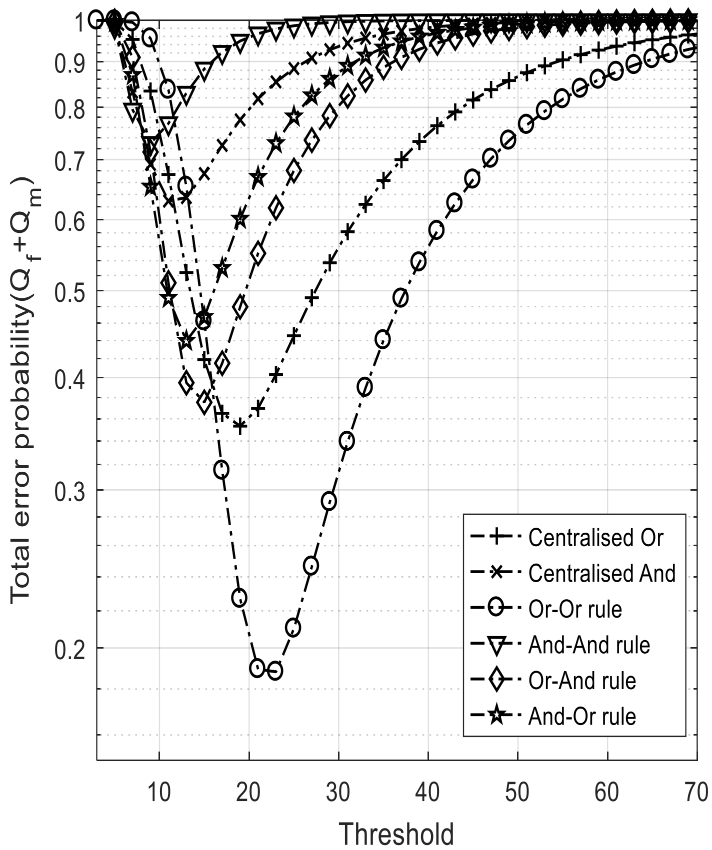

Figure 4.10 Performance of distributed and centralised CSS with respect to total probability and threshold

Results published in the paper: "Cluster-based distributed cooperative spectrum sensing over Nakagami fading using diversity reception." IET Networks (2019). DOI: 10.1049/iet-net.2018.5002

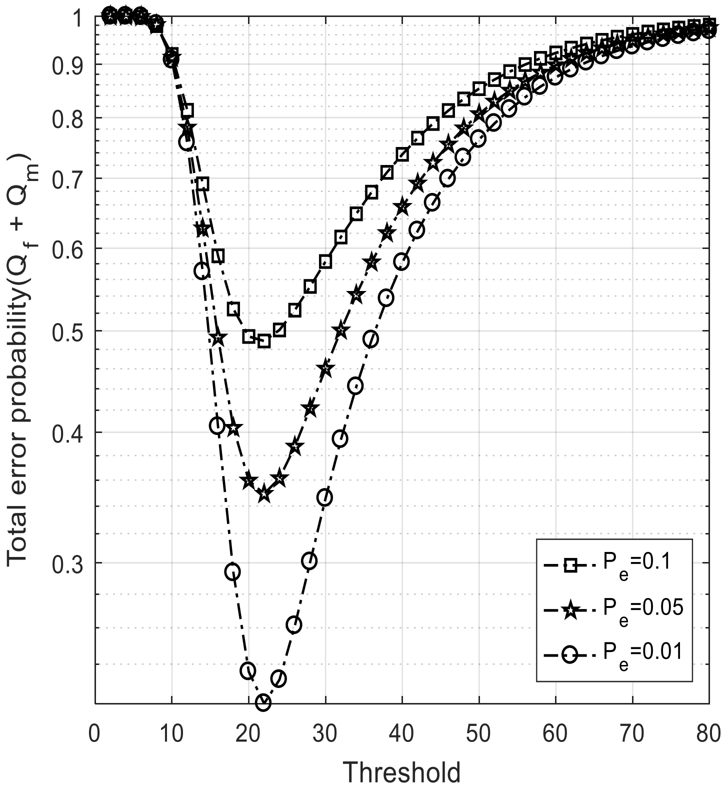

Figure 4.11 Performance of distributed CSS with OR-OR fusion under imperfect reporting

Figure 4.10 show threshold (λ) vs. Total error probability ($Q_f + Q_m$) plot for both centralised and distributed CSS. It can be observed from Figure 4.10 that for a given value of threshold, OR-OR fusion rule has the minimum total error probability. For OR-OR fusion high value of threshold is required, hence there is less chances of false alarm due to any noise.

Figure 4.11 show the variation of Total error probability of OR-OR fusion threshold under noisy reporting conditions. It is clear from Figure 4.11that total error probability ($Q_f + Q_m$) is minimum when probability of error in the reporting channel is low and it is maximum when probability of error is high. Therefore, it is necessary to consider noisy reporting while designing CSS CR system.

Figure 4.12 show the Complimentary ROC plot for OR-OR fusion at SNR = 10dB over Nakagami (m = 2) fading when both number of clusters and number of users in the cluster increases from 2 to 5.

Results published in the paper: "Cluster-based distributed cooperative spectrum sensing over Nakagami fading using diversity reception." IET Networks (2019). DOI: 10.1049/iet-net.2018.5002

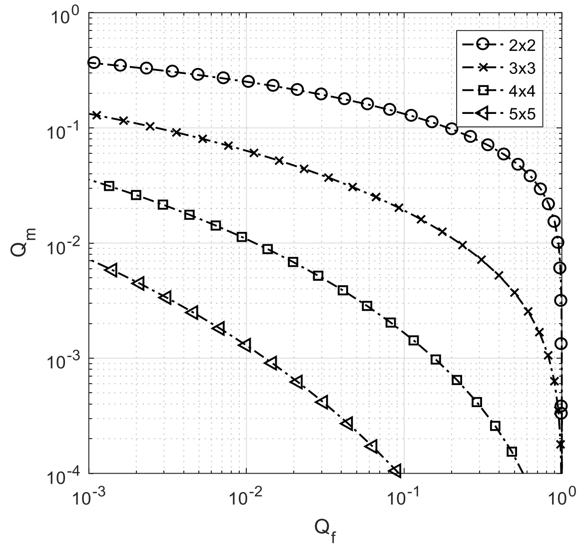

Figure 4.12 Complimentary ROC plot for OR-OR fusion at SNR=10dB for different number of clusters and number of users in the cluster

Figure 4.12 show that for a given false alarm probability, miss detection decreases when number of clusters and number of users in the clusters both increases. Hence detection probability increases. For false alarm probability 0.001, detection probability increases 25% when total number of CR users increases from 4 to 9 and it increases 32% when total number of CR users increases from 4 to 16.

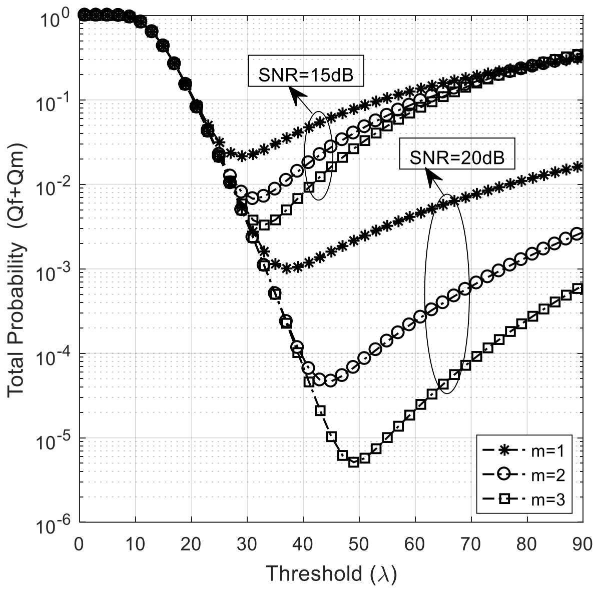

Figure 4.13 Total probability vs. Threshold curve over Nakagami fading channel for different m and for different SNR

Results published in the paper: "Performance evaluation of distributed CSS with clustering of secondary users over fading channels." International Journal of Electronics Letters 6, no. 3 (2018): 288-301. DOI: 10.1080/21681724.2017.1357762

Figure 4.13 show total probability vs. threshold curve over Nakagami fading channel for m = 1, 2, 3 and SNR = 15dB and 20dB. It is observed from Figure 4.13 that at lower values of threshold, the miss detection is less but false alarm is high. At higher values of threshold situation, reverses and we get large miss detection and small false alarm. Thus it is possible to find out optimum value of threshold at which total error probability is minimum. The minimum detection threshold is 29, 31, 33 for SNR = 15dB at m = 1, 2, 3 respectively. This optimum value of threshold, however depends on fading severity parameter and SNR value. As the value of m or SNR increases, optimum value of detection threshold also increases

Diversity reception improves the performance of the cluster based distributed CSS. This is investigated in Figure 4.14 and Figure 4.15.

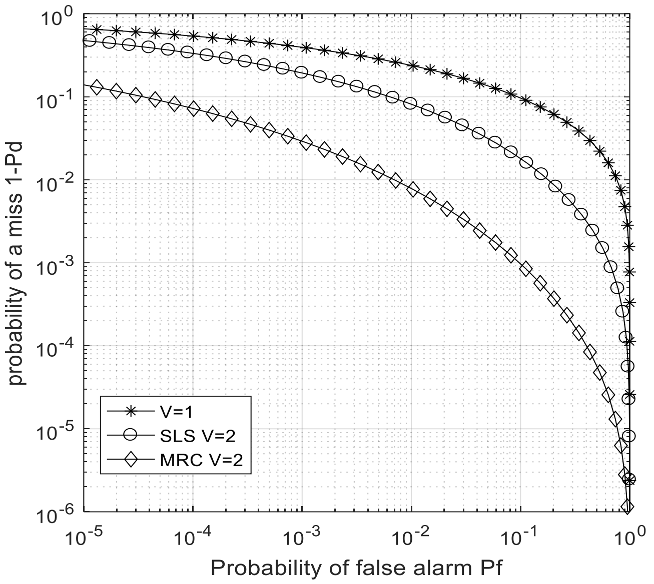

Figure 4.14 Performance of OR-OR fusion using SLS and MRC diversity scheme (V is the number of diversity branch)

Figure 4.14 shows complimentary ROC performance of OR-OR fusion with SLS and MRC reception over Nakagami fading. V = 1 represents no diversity case and V = 2 is dual branch combiner for both the combining schemes. Simulation results justifies the analytical equations presented in the section 4. The best performance is observed for MRC diversity because in MRC the weights are obtained which maximizes the output SNR. There is roughly an improvement of one order magnitude in P_m Compared to no diversity case. For false alarm probability of 0.01, P_d is equal to 0.76, 0.91 and 0.99, for no diversity, with SLS and with MRC diversity respectively.

Results published in the paper: "Cluster-based distributed cooperative spectrum sensing over Nakagami fading using diversity reception." IET Networks (2019). DOI: 10.1049/iet-net.2018.5002

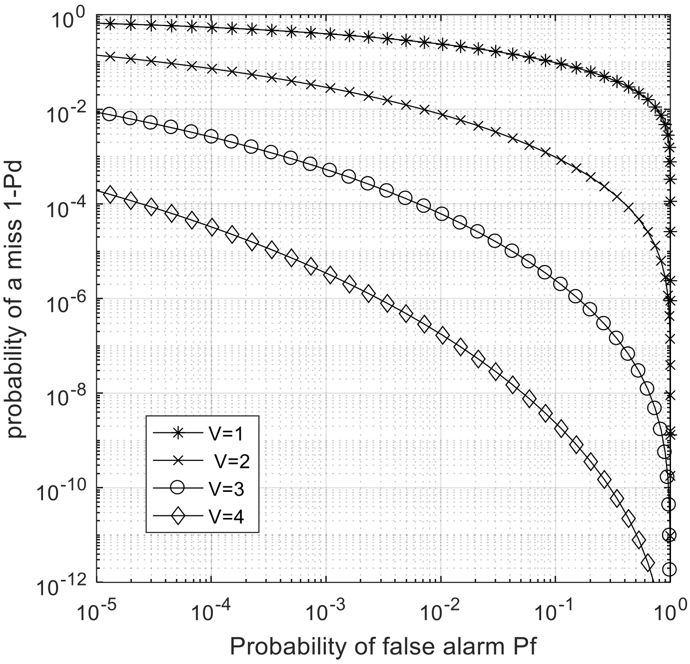

Figure 4.15 Performance of OR-OR fusion using MRC diversity scheme with different V

Figure 4.15 shows complimentary ROC plot of OR-OR fusion using MRC diversity scheme with different number of diversity branches V = 1 to 4. It can be observed that as number of diversity branches increases probability of detection also increases. MRC combiner with V = 2 provides gain of roughly one order of magnitude from probability of miss perspective, compared to V = 1 and more than one order of magnitude for V = 3, compared to V = 2. The slope of the curve gets steeper as number of diversity branches increases.

Table 4:1 Performance of OR-OR fusion with respect to number of MRC diversity branch (V)

False alarm probability (P_f) = 0.1				
	V=1	V=2	V=3	V=4
Probability of Miss (P_m)	0.0907	0.00084	1.96×10^{-6}	1.78×10^{-9}

4.6 Conclusion

In this chapter, distributed CSS with clustering is presented over Rayleigh, Nakagami and Rician fading channels. Firstly, centralised CSS is discussed with different fusion rules and then performance is compared with cluster-based distributed CSS with four different fusion rules. Simulation results show that OR-OR fusion rule of distributed CSS outperforms the other

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fusion rules and it performs better then centralised CSS. To further improve the performance of distributed CSS, SLS and MRC diversity schemes are employed and results show that detection performance can be improved by using diversity. It is clear from the results that if number of CR users and number of clusters increases, user cooperation increases and chances of detection of empty spectrum increases. However, with the increase of both L and M, energy consumption and overhead of the network increases. Thus, a comprehensive metric is required, which can measure performance of CSS taking account of achievable throughput, detection accuracy, and overall energy consumption.

In the next chapter, EE of non-cluster based CSS is measured and optimized, taking both fusion rule threshold and sensing time under consideration.

CHAPTER 5: JOINT SENSING TIME AND FUSION RULE THRESHOLD OPTIMIZATION FOR ENERGY EFFICIENT CSS

Cooperative spectrum sensing can mitigate the effects of multipath and shadowing, but in CSS energy resources become precious when the SUs are battery operated. So it becomes important to use their energy efficiently. The EE is defined as the rate of data transmission per unit energy. EE is a comprehensive metric, which represents the overall performance of the CR because it jointly takes into account of achievable throughput, detection accuracy, and overall energy consumption. In CSS, the number of cooperative users, fusion rule threshold, transmission power and sensing time affects the EE of the CSS. In this chapter, effect of fusion rule threshold and sensing time is investigated and an iterative algorithm is proposed to determine joint optimal fusion rule threshold and sensing time that maximizes the EE of CSS.

5.1 System Model:

If there are ‘N’ number of CR users and single PU with a common fusion centre which manages the CR network, then each SU detects the presence of PU using energy detector (ED). In an energy detector signal x(t) is given as input and it gives an output which is in the form of binary decision with reference to presence of PU. There are two hypothesis as given in equation chapter 4 (4.1).

SUs will sense the presence of PU and transmit their decision to base station. The base station which acts as fusion center (FC) will make the final decision based on the received information from the SUs. One of the SUs will be allowed to transmit data if the PU is detected to be absent, otherwise, SU is not allowed to use the frequency spectrum. The frame structure of the CR is as shown in Figure 5.1. Here T represents total frame time, τ_s represents sensing time, τ_r represents reporting time of each SU to report their decision FC.

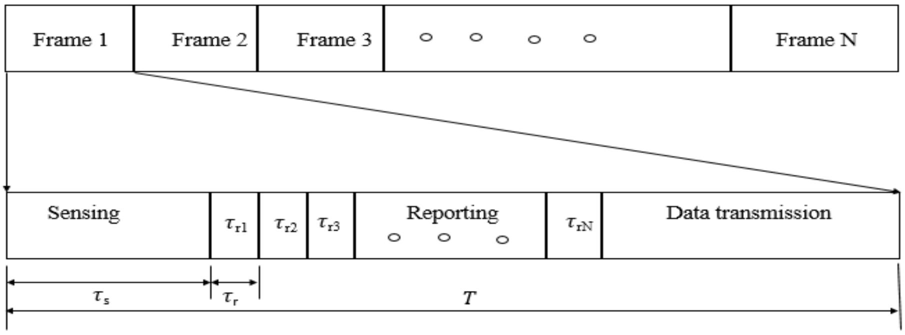

Figure 5.1 Frame structure of CSS [107]

The distances between CR users are considered small compared to the distances between the PU and CR users so that CR users have same average SNR (γ_1) of the primary transmission. If energy detector is used for each CR user to detect the presence of the PU, the false alarm probability at j[th] CR user for given threshold ε_j can be given by [107].

$$P_f{}^j = Q\left(\left(\frac{\varepsilon_j}{\sigma_n{}^2} - 1\right)\sqrt{\tau_s\, f_s}\right), \forall\, j = 1 \cdots N \tag{5.1}$$

Where f_s is the sampling frequency, $\sigma_n{}^2$ is noise power spectral density received at CR users and $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-\frac{t^2}{2}}\, dt.$ If PU signal is a complex- valued PSK signal, the detection probability at j[th] CR user is given by [107]:

$$P_d{}^j = Q\left(\left(\frac{\varepsilon_j}{\sigma_n{}^2} - \gamma_1 - 1\right)\sqrt{\frac{\tau_s\, f_s}{2\gamma+1}}\right), \forall\, j = 1 \cdots N \tag{5.2}$$

If a common threshold ε is used for all CR users then $P_f{}^j = P_f$ and $P_d{}^j = P_d$. For fixed number of CR users and target false alarm probability when base station uses k out of N fusion rule, the overall detection and false alarm probabilities are given by

$$Q_f(N, \varepsilon, k, \tau_s) = \sum_{j=k}^{N} \binom{N}{j} P_f{}^j \left(1 - P_f\right)^{N-j}, \tag{5.3}$$

$$Q_d(N, \varepsilon, k, \tau_s) = \sum_{j=k}^{N} \binom{N}{j} P_d{}^j \left(1 - P_d\right)^{N-j}, \tag{5.4}$$

5.2 Design Formulation Problem:

The design problem can be setup by first considering total energy consumption and the average throughput in the CSS.

5.2.1 Energy Consumption

There are four possible cases between the activity of SUs and PU.

Case 1: Let PU is present, and SUs detects it. In this case, no useful data can be transmitted as the PU occupies the spectrum. Total energy consumed in this case, is given by

$$E_1(\tau_s) = N(\tau_s\theta_s + \tau_r\ \theta_t), \tag{5.5}$$

where θ_s and θ_t are sensing power and transmission power of each SU respectively.

Case 2: PU is absent, and SU detects it as a present. In this case also, no data can be transmitted and total energy consumed will be the same as in the previous case.

Case 3: PU is present, and SU miss detects it. In this case, data can be transmitted but it can interfere with the PU signal and SU will not able to detect it successfully, so the total energy consumed is given by

$$E_2(\tau_s) = N\tau_s\ \theta_s\ \ + \tau_d\ \theta_t\,, \tag{5.6}$$

where τ_d is the data transmission time ($\tau_d\ = T - \tau_s\ - N\tau_r\ \approx T - \tau_s$).

Case 4: PU is absent, and the SU successfully detects it. In this case, data can be transmitted, and energy consumption is the same as in the previous case.

The total energy consumption $\mathbb{E}$ can be determined by considering equations (5.5), and (5.6)

$$\mathbb{E}(N, \varepsilon, k, \tau_s) = \ N\ \tau_s\ \theta_s\ + N\ \tau_r\ \theta_t\ + \left(P_0\left(1 - Q_f(k, \tau_s)\right) + P_1\left(1 - Q_d(k, \tau_s)\right)\right)\tau_d\ \theta_t\ , \tag{5.7}$$

where P_1 is the probability of the PU being busy and P_0 is the probability of PU being idle.

5.2.2 Throughput

Throughput should be determined for two cases. In the first case when PU is absent and SUs successfully detected it. In the second case when PU is present but SUs miss detects it. Mathematically the overall throughput for both the cases is given by [94]

$$\mathbb{R}(N, \varepsilon, k, \tau_s) = P_0\, C_0\left(1 - Q_f(k, \tau_s)\right)\tau_d\ + P_1\, C_1\big(1 - Q_d(k, \tau_s)\big)\tau_d\,, \tag{5.8}$$

where C_0, and C_1 are the achievable data rate when CR user transmit data under no PU interference and with PU interference respectively. In the second case, an SU will start transmitting data but its signal can be interfered by the PUs signal. In this case, it is assumed that SUs receiver cannot decode data due to PUs interference. Since data is successfully transmitted in the fourth stage, throughput ($\mathbb{R}$) is given by

$$\mathbb{R}(N, \varepsilon, k, \tau_s) \approx P_0 \left(1 - Q_f(k, \tau_s)\right) \tau_d \, C_0, \tag{5.9}$$

C_0 is the channel capacity over the period τ_d , it can be calculated as $C_0 = B \log_2 \left(1 + \frac{\alpha_r}{\Gamma}\right)$, where B is the channel bandwidth and Γ is the noise power over B.

5.2.3 Energy Efficiency

The EE (ξ) is defined as the rate of successful data transmission per unit energy consumed which can be given by

$$\xi(N, \varepsilon, k, \tau_s) = \frac{\mathbb{R}(N,\varepsilon,k,\tau_s)}{\mathbb{E}(N,\varepsilon,k,\tau_s)}. \tag{5.10}$$

The design parameters k and τ_s have the direct impact on the EE. The design problem to maximize EE can be written as

Find: (τ_{s0}, k_0)

Max: $\xi(N, \varepsilon, k, \tau_s)$

Subject to: $P_f \le \bar{P}_f, \tau_s \ge 0, 0 \le k \le N, \quad 0 \le N \le N_{max}$ (5.11)

where τ_{s0} and k_0 are the optimum values of sensing time and fusion rule threshold respectively, $\bar{P}_f$ is the target probability false alarm and N_{max} is the maximum allowable SUs.

5.3 Proposed Algorithm:

The first constraint of the optimization problem always grants that $P_f = \bar{P}_f$. We can determine probability of detection using equation (5.1) which gives

$$Q^{-1}(\bar{P}_f) = \left(\frac{\varepsilon_j}{\sigma_n^{2}} - 1\right)\sqrt{\tau_s \, f_s}\,, \tag{5.12}$$

Using equation (5.2)

$$P_d(\tau_s) = Q\left(\frac{1}{\sqrt{2\gamma+1}}\left(Q^{-1}(\bar{P}_f) - \sqrt{\tau_s \, f_s}\,\gamma_1\right)\right). \tag{5.13}$$

From equation (5.13), $P_d(\tau_s)$ is a concave function of τ_s (proof is given in appendix A). However, τ_s should be limited to be within some interval $[\tau_{min}\ ,\ \tau_{max}]$. The upper bound can be calculated by letting $P_d\,(\tau_s\,) > 0.5$ therefor from (5.13), $\tau_{max} = \left(\frac{Q^{-1}(\bar{P}_f\,)}{\gamma\sqrt{f_s}}\right)^2$ and lower bound can be taken as $\tau_{min} = 0$. The common threshold ε can be calculated from target false alarm probability and if the number of CR users are fixed, the EE can be given as

$$\xi(k,\tau_s) = \frac{\mathbb{R}(k,\tau_s)}{\mathbb{E}(k,\tau_s)}. \tag{5.14}$$

Now optimization problem can be rewritten as

$$\begin{aligned} &\text{Find: } (\tau_{s0}, k_0) \\ &\text{Max: } \ \xi(k,\tau_s) \\ &\text{Subject to: } \ \tau_{min} \le \tau_s \le \tau_{max}\,,\ 0 \le k \le N \end{aligned} \tag{5.15}$$

Proposition 5.1: For any given ‘N’ CR users and k, there is an optimal sensing time τ_s (i.e., τ_{s0}) that maximizes the $\xi(k,\tau_s)$ where $\tau_{s0} \in [\tau_{min}\ ,\ \tau_{max}\,]$.

Proof: To simplify the subsequent derivation, we denote $Q_f(\tau_s)$ and $\xi(k,\tau_s)$ as Q_f and ξ respectively. If we assume$\left(1 - Q_d(\tau_s)\right) \approx 0$, since detection probability should be greater than 0.9, and $\tau_r \ll (T - \tau_s)$ we can calculate $\mathbb{E}$ in equation (5.7) as

$$\mathbb{E} = N\,\tau_s\,\theta_s\ + P_0\,\theta_t\ (T-\tau_s)\left(1-Q_f\right). \tag{5.16}$$

The EE can be determined from equation (5.14) using equation (5.8) and equation (5.9) as

$$\xi = \frac{N\,\tau_s\,\theta_s\ +P_0\,\theta_t\ (T-\tau_s)\left(1-Q_f\right)}{P_0\,C_0\left(1-Q_f\right)(T-\tau_s)} = \frac{A\tau_s}{\left(1-Q_f\right)(T-\tau_s)} + B, \tag{5.17}$$

where $A = \frac{N\,\theta_s}{P_0\,C_0}$ and $B = \frac{\theta_t}{C_0}$

Since ξ is a continuous function of τ_s in the given interval the first derivative of ξ w.r.t. τ_s is given as $\dot{\xi} = \frac{AT\left(1-Q_f\right)-\tau_s(\tau_s-T)\dot{Q_f}}{(T-\tau_s)^2(1-Q_f)^2}$, (5.18)

where $\dot{Q_f}$ is the first partial derivative of Q_f w.r.t τ_s. When $\tau_{min} \le \tau_s \le \tau_{max}$, since Q_f is convex function thus $\dot{Q}_f < 0$, $\forall\,\tau_s$ also $\dot{Q}_f \le Q_f$ and $A > 0$ therefore $\dot{\xi} > 0$.

Similarly if we take second partial derivative of ξ w.r.t. τ_s it can be given by

$$\ddot{\xi} = \frac{A(\ddot{Q}_f\left(T^2\tau_s-2T\tau_s{}^2+\tau_s{}^3-Q_f\tau_s(T-\tau_s)^2\right)+\dot{Q}_f\left(2\tau_s(T-\tau_s)^2\dot{Q}_f+2T(T-\tau_s)-2TQ_f(T-\tau_s)\right)-4TQ_f+2TQ_f{}^2+2T)}{(T-\tau_s)^3(1-Q_f)^3} \tag{5.19}$$

Which can further written as $\ddot{\xi} = \frac{A(\ddot{Q}_f C_1 + \dot{Q}_f C_2 + C_3)}{(T-\tau_s)^3(1-Q_f)^3}$

where $C_1 = \left(T^2\tau_s - 2T{\tau_s}^2 + {\tau_s}^3 - Q_f\tau_s(T-\tau_s)^2\right)$

$$C_2 = \left(2\tau_s(T-\tau_s)^2\dot{Q}_f + 2T(T-\tau_s) - 2TQ_f(T-\tau_s)\right)$$

$$C_3 = -4TQ_f + 2T{Q_f}^2 + 2T$$

It is difficult to analyse equation (5.19) but for given conditions $\dot{Q}_f < 0$, $\ddot{Q}_f > 0 \ \ \forall \tau_s$, $\dot{Q}_f \leq Q_f$ and for given interval $C_1 < 0$, $C_2 > 0$ and $C_3 > 0$. Since $|C_1| > |C_3|$ and $|C_2| > |C_3|$ it can be proved that $\ddot{\xi} < 0$ therefor $\xi(k,\tau_s)$ is a concave function of τ_s and we can use bisection method to determine optimal τ_s i.e. τ_{s0}.

Table 5:1 Proposed Iterative Algorithm to find optimum parameters

Initialize T, N, f_s, θ_s , θ_t , τ_r , α, $\bar{P}_f$

Calculate τ_{min} , and τ_{max}

1. while $Q_d < \alpha$ and k ≤N do
2. Compute τ_{s0} = bisect ($\xi(k,\tau_s), \tau_{min}, \tau_{max}$) such that $\dot{\xi}(k,\tau_s) = 0$
3. Update k
4. $\tau_{s0} = \tau_1 + \epsilon$
5. If $\xi(k,\tau_{s0}) \geq \xi(k,\tau_1)$
6. $\tau_{min} = \tau_1$
7. $else$
8. $\tau_{max} = \tau_1$
9. end if
10. end while
11. Return $k_{opt} = k_0$, $\tau_{opt} = \tau_{s0}$

The fusion rule threshold (k) is an integer number, which means $\xi(k,\tau_s)$ is not a continuous function of k. Thus it is not feasible to derive an analytical solution for optimum k. Hence a joint optimization Fusion rule threshold (k) and Sensing time (τ_s) is proposed to maximize $\xi(k,\tau_s)$. Bisection algorithm is used to optimize EE since it is less complicated and requires less iterations. The results obtained from table 5.1 is further analysed in numerical results section.

Computational complexity of the proposed algorithm can be determined by first considering the fusion rule threshold. Half interval search method is used to determine the optimum fusion rule threshold (k_0) which has a computational complexity of $O(Log_2(N))$ where N is the total number of SUs. To determine the value of optimum sensing time (τ_s), bisection method is used. In the worst case scenario, the bisection method has computational complexity of $O(Log_2\left(\frac{\tau_{max}-\tau_{min}}{\mu}\right))$, where μ is the allowable tolerance. Therefore, the overall computational complexity of the proposed algorithm is $O\left(Log_2(N)Log_2\left(\frac{\tau_{max}-\tau_{min}}{\mu}\right)\right)$.

5.4 Numerical Results:

The simulation parameters are taken as N = 20, T = 50 ms, $\bar{P}_f$ = 0.1, f_s = 6MHz, $\theta_s = 0.1, W$, $\theta_t = 2W,\ \sigma_n{}^2$ =1, $\tau_r = 10\mu s,\ \alpha = 0.9$.

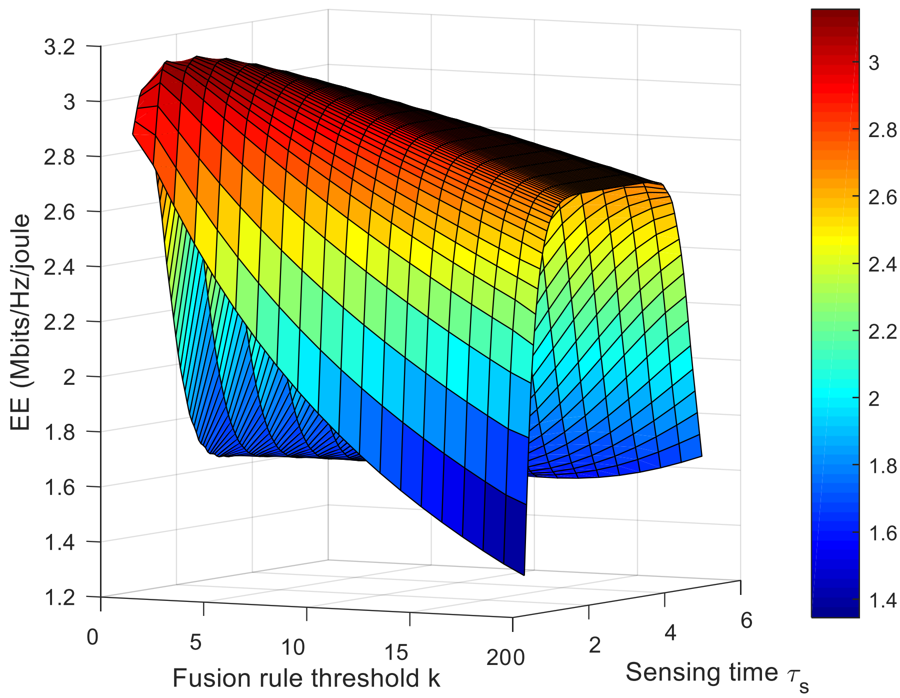

Figure 5.2 Energy Efficiency (ξ) vs. Fusion rule threshold (k) and Sensing time (τ_s) at SNR = -18dB

A 3-D plot of EE and its contour are demonstrated in Figure 5.2 and 5.3, respectively. Figure 5.2 shows variation of EE with sensing time and fusion rule threshold at SNR = -18dB. It shows that EE is a concave function of both sensing time and fusion rule threshold and there is a

Results published in the paper: "Joint sensing time and fusion rule threshold optimization for energy efficient CSS in cognitive radio sensor networks." International Journal of Communication Systems 31, no. 18 (2018): e3820. DOI: 10.1002/dac.3820

unique optimum point i.e. joint optimum k_0 and τ_{s0} that maximizes the EE. In Figure 5.3 contour of Figure 5.2 is drawn for better understanding of optimum values. The nature of graph in Figure 5.2 and 5.3 is further explained in Figure 5.4 and Figure 5.5. Quantitatively, k_0 = 4, τ_{s0} = 0.841 ms, and ξ_{max} = 3.15 Mbits/Hz/joule when SNR = -18dB and k_0 = 4, τ_{s0} = 0.391 ms, and ξ_{max} = 3.23 Mbits/Hz/joule when SNR = -16dB. From Figure 5.2 the optimum k_0 and τ_{s0} are same as obtained from algorithm proposed in Table 5.1.This shows that from the proposed algorithm the optimum sensing time and fusion rule threshold can be obtained.

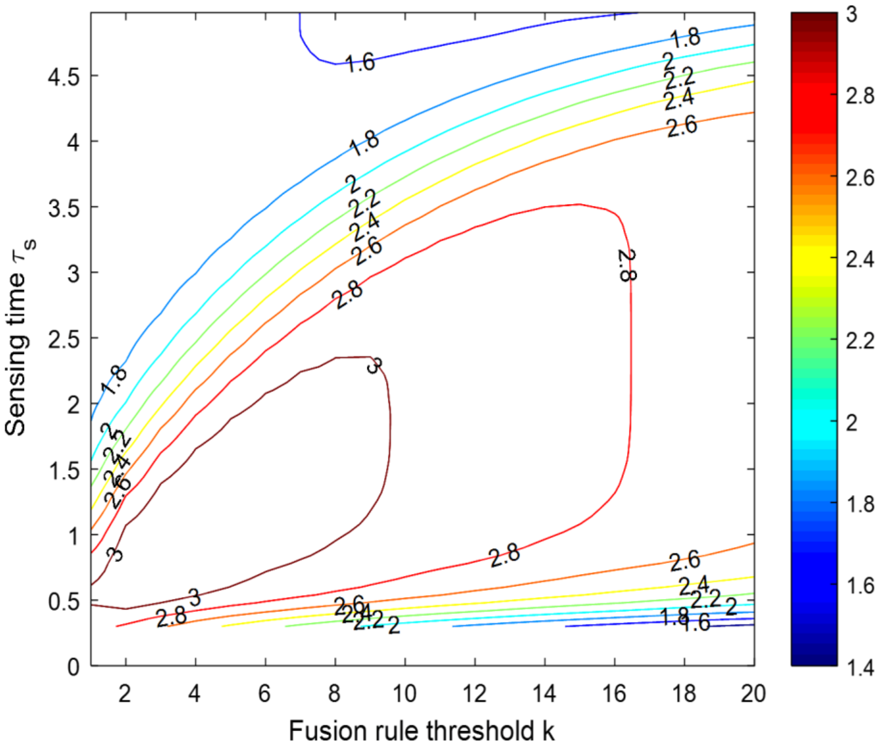

Figure 5.3 Contour graph of Energy Efficiency (ξ) vs. Fusion rule threshold (k) and Sensing time (τ_s) at SNR = -18dB

In Figure 5.4, EE (ξ) is plotted against fusion rule threshold (k) for different SNR. In Figure 5.4 detector threshold (ε) is fixed for target false alarm probability ($\bar{P}_f$) =0.1 and sensing time (τ_s) is fixed at optimum values obtained from Table 5.1. EE is concave function of k because at lower values of k, false alarm is high and at higher values of k, detection probability is low. It is observed from Figure 5.4 that optimization of fusion rule threshold (k) is important as EE is almost double at optimum fusion rule threshold (k = 4), compared to k= 20 (AND rule) and also at k=1 (OR rule), EE is =2.775Mbits/Hz/joule at SNR =-16dB which is 16.4% less than the optimum value. Optimization of fusion rule threshold is done at the fusion center unlike optimizing detector threshold hence it does not require any feedback channel.

Results published in the paper: "Joint sensing time and fusion rule threshold optimization for energy efficient CSS in cognitive radio sensor networks." International Journal of Communication Systems 31, no. 18 (2018): e3820. DOI: 10.1002/dac.3820

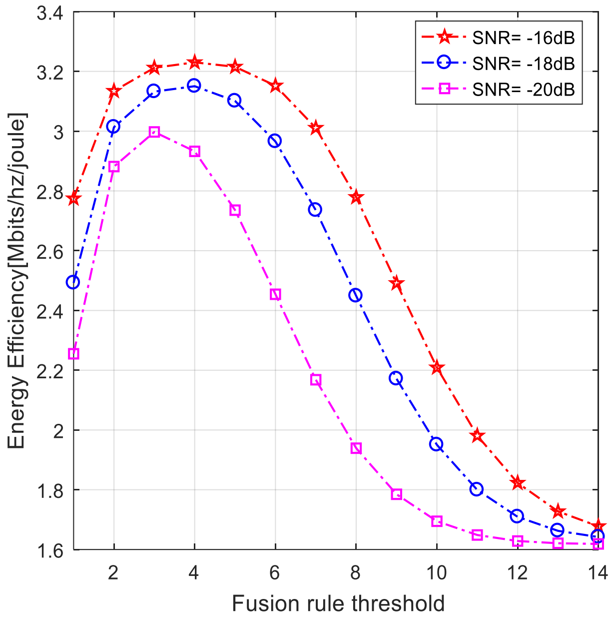

Figure 5.4 Energy Efficiency (ξ) vs. Fusion rule threshold (k) at optimum Sensing time for different SNR

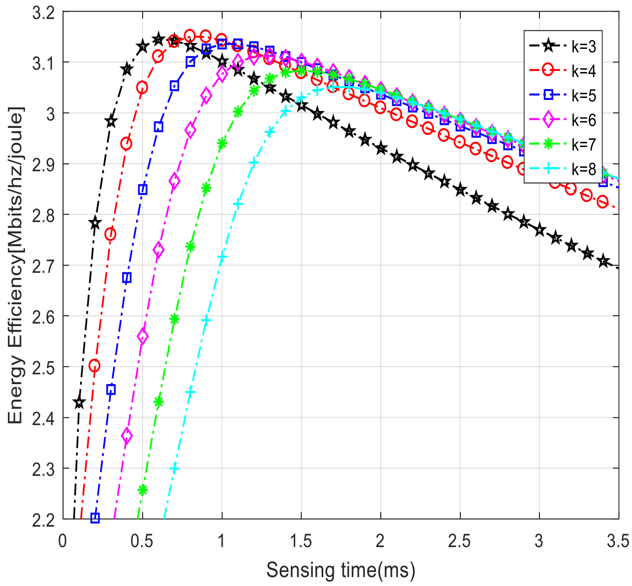

Figure 5.5 Energy Efficiency (ξ) vs. Sensing time (τ_s) at different fusion rule threshold (k) for SNR =-18 dB

Table 5:2 Comparison with previous existing work

Work	Frame time (T)	SNR	Optimum fusion rule threshold	EE at optimum fusion rule threshold
[107]	50 ms	-18 dB	4	3.18 Mbits/Hz/joule
Proposed	20 ms	-18 dB	6	190bit/Hz/joule

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Table 5.2 compares the result of Figure 5.4 with previous existing result.

In Figure 5.5 EE (ξ) is plotted against Sensing time (τ_s) for SNR = -18dB at different fusion rule threshold (k). In Figure 5.5 initially, when sensing time is increased, the EE increases this means the larger energies are consumed during sensing stage and loss in shorter transmission time is outweighed by the improvement in the sensing performance. However, when sensing time further increases, the EE decreases as it is no longer worth to get better sensing performance as very less transmission time is left. It is observed that EE is maximum at $k_0 = 4$, $\tau_{s0} = 0.841$ ms.

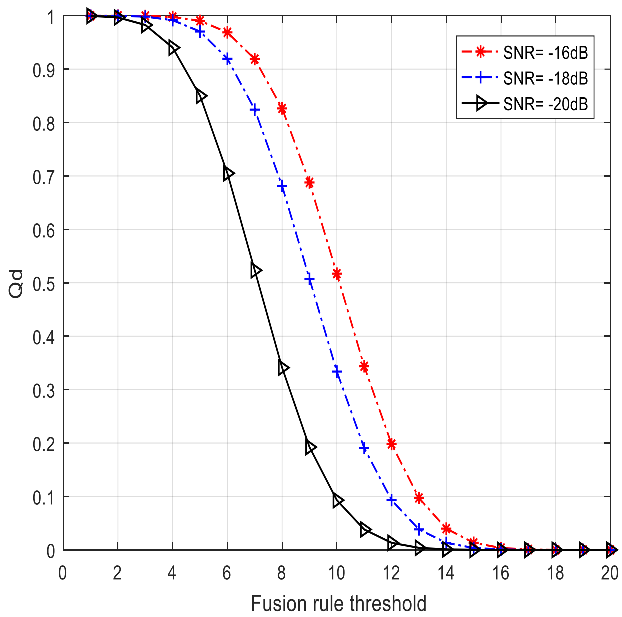

Figure 5.6 Probability of detection (Q_d) vs. Fusion rule threshold (k) at optimized sensing time (τ_s) for different SNR

In Figure 5.6, the global probability of detection (Q_d) for 'N' CR is plotted against fusion rule threshold at optimum sensing time (τ_s). At the optimum value of fusion rule threshold $k_0 = 3$ and 4, the global detection probability is more than 90%. Hence, the values of detection probability in all cases satisfy the target detection probability of 0.9.

In Figure 5.7, EE is plotted against SNR for two cases. **In the first case** sensing time (τ_s) is optimized and fusion rule threshold (k) is kept fixed. **In the second case** both k and τ_s are jointly optimized. It is observed from Figure 5.7 that at SNR = -24dB, EE is 1.0 Mbits/Hz/joule higher for second case compared to first case. At SNR = -16dB, EE is 0.4 Mbits/Hz/joule higher for second case compared to first case. At low SNR region joint optimization performs

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better compared to single optimization. Result shows that this joint optimization performs better compared to [107] at higher SNR.

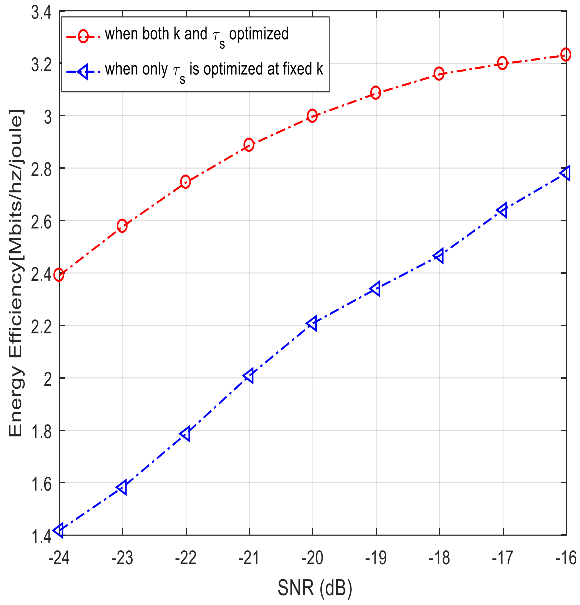

Figure 5.7 Energy Efficiency ξ at different SNR regions for joint and single optimization

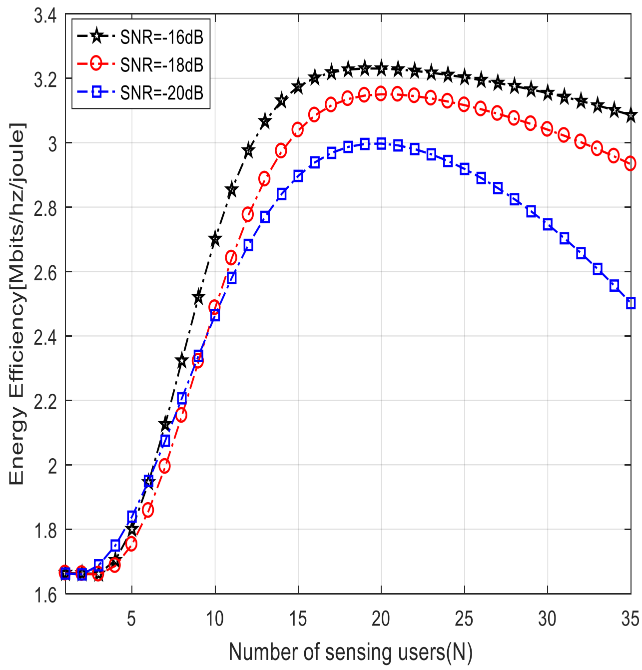

Figure 5.8 Energy Efficiency (ξ) vs. Number of sensing users (N) at different optimized k and τ_s

In Figure 5.8 EE is plotted against number of sensing users (N) when k and τ_s are jointly optimized. When the number of sensing users varies instead of τ_s, the graph shows the same

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trend as in Figure 5.5 because increasing the number of sensing users has similar effects as increasing the sensing time, Energy consumption increases and transmission time decreases although sensing performance improves.

In Figure 5.9, P_d and parameter Z is plotted against sensing time (τ_s) for different SNR values. Here parameter $Z = \left(\frac{1}{(\sqrt{\tau_s})} + B\left(A - B\sqrt{\tau_s}\right)\right)$, where $A = \frac{Q^{-1}(\bar{P}_f)}{\sqrt{2\gamma+1}}$ and $B = \frac{\gamma\sqrt{f_s}}{\sqrt{2\gamma+1}}$. In appendix A, it is proved that P_d is a concave function of τ_s under the condition that $Z > 0$. It is observed from Figure 5.9 that P_d is a concave function of τ_s for the given condition. For SNR = -18dB the P_d curve is concave until $Z > 0$ and than it becomes flat. Similar trend is observed for SNR = -20dB.

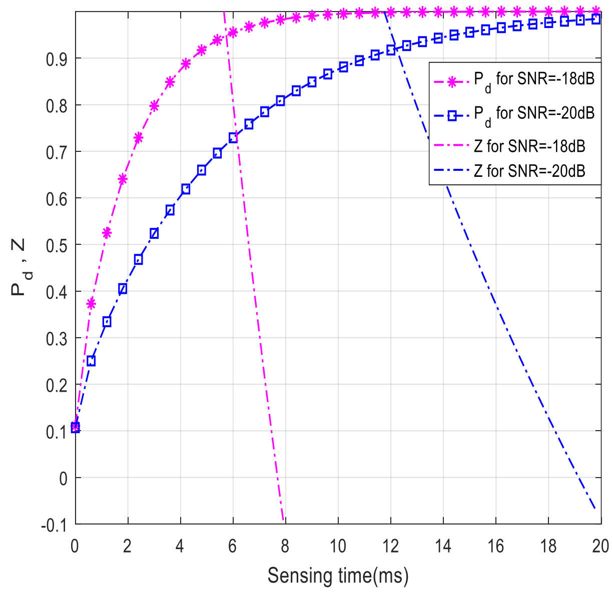

Figure 5.9 Probability of detection (P_d) and parameter Z vs. sensing time (τ_s) at different SNR

5.5 Conclusion

The effect of varying the sensing time and fusion rule threshold on EE has been investigated. The investigations have shown that there is an optimal value of fusion rule threshold and sensing time at which the EE is maximum. Quantitatively optimum sensing duration (τ_{s0}) = 0.841ms and fusion rule threshold (k_0) = 4 at SNR = -18dB. Maximum EE at optimal point is (ξ_{max}) = 3.15 Mbits/Hz/Joule. The analysis and formulation of design problem has been provided. To determine the joint design parameters (i.e. fusion rule threshold and sensing time) that maximize the EE, a single iterative algorithm has been proposed. Results show that

Results published in the paper: "Joint sensing time and fusion rule threshold optimization for energy efficient CSS in cognitive radio sensor networks." International Journal of Communication Systems 31, no. 18 (2018): e3820. DOI: 10.1002/dac.3820

proposed work satisfy the detection accuracy metric. Proposed algorithm gives better performance at higher SNR compared to existing work since optimizing of detector threshold does not affect EE at high SNR.

In the next chapter, EE is measured for CBCSS and an iterative method is proposed which finds the optimum number of clusters and number of users in a cluster, which maximizes the EE.

CHAPTER 6: CLUSTER-BASED ENERGY EFFICIENT CSS FOR COGNITIVE RADIO NETWORKS

In the previous chapter EE is measured for non cluster based CSS. Clustering can maximize the EE by minimizing total energy consumption. In CSS, the parameters which affect the EE of the system are, number of cooperative users, fusion rule, transmission power and sensing time. In this chapter, effect of fusion rule on EE is investigated for centralized CSS and a cluster-based CSS which has been proposed with four fusion rules OR-OR, AND-OR, OR-AND, AND-AND. An iterative algorithm has been proposed which finds the optimum number of clusters and number of users in a cluster, which maximizes the EE.

6.1 System Model:

6.1.1 Centralized CSS

The system model for the centralized CSS is same as presented in section 5.1 of chapter 5. A CR network with 'N' SUs and a base station is considered. The frame structure of the CR is same as in Figure 5.1 in chapter 5.

Reporting time $\tau_r \ll T$, is considered then normalized sensing time is define as $\tau = \frac{\tau_s}{T}$ also data transmission time can be written as $\tau_d = (1-\tau)T$. If energy detector is used for each CR user to detect the presence of the PU, the false alarm probability in equation (5.1) can be written as:

$$P_f{}^j = Q\left(\left(\frac{\varepsilon_j}{\sigma_n{}^2} - 1\right)\sqrt{\tau\, f_s\, \mathrm{T}}\right), \forall\, j = 1 \cdots N \tag{6.1}$$

In addition, the detection probability in equation (5.2) can be written as

$$P_d{}^j = Q\left(\left(\frac{\varepsilon_j}{\sigma_n{}^2} - \gamma_1 - 1\right)\sqrt{\frac{\sqrt{\tau\, f_s\, \mathrm{T}}}{2\gamma+1}}\right), \forall\, j = 1 \cdots N \tag{6.2}$$

If we consider detection probability P_d to be equal to target detection probability $\bar{p}_d$. The false alarm probability in equation (6.1) can be written as

$$P_f(\tau) = Q\left(\sqrt{2\gamma_1 + 1}\; Q^{-1}(\bar{p}_d)\sqrt{\tau\, f_s\, \mathrm{T}}\right), \forall\, j = 1 \cdots N \tag{6.3}$$

The global probability of false alarm and detection probability is determined by the base station using k out of N fusion rule. These are given in equation (5.3) and equation (5.4) in chapter 5. When k = 1, it is OR fusion rule and when k = N, it is AND fusion rule.

6.1.2 Cluster-based CSS:

The structure of cluster-based CSS is shown in Figure 6.1. It is assumed that there are L number of clusters and in each cluster, there are M SUs. So the total number of CR users in the system is M×L. All the CR users are assumed to be grouped into small clusters. For each cluster, a SU is set as a cluster head (CH).

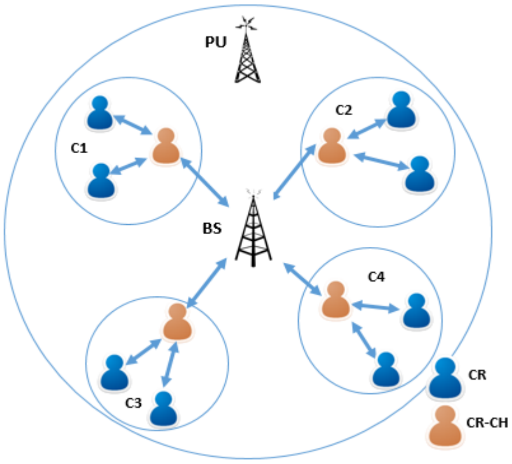

Figure 6.1 Cluster-based CSS

In cluster based CSS, each SU performs the local spectrum sensing then this information is exchanged with the CH of the same cluster by some fusion rule to decide the presence of the PU. Thus each cluster has its final decision of the presence of PU. Now there are many clusters in the network, they report their information to the base station (BS) and base station fuses the information by a fusion rule to finally decide the presence of PUs. The information exchanges between clusters through the cluster heads (CH), which is responsible for data collection, information circulation and network management [124]. Non cluster heads are responsible mainly for sensing and collecting information from surroundings.

There are four fusion possible for this cluster based CSS, OR-OR fusion, OR-AND fusion, AND-OR fusion & AND-AND fusion. The probability of false alarm, detection probability and miss detection probability of the four fusion rules are given in section 4.2 of chapter 4.

6.2 Energy Efficiency of Cluster-based CSS:

6.2.1 Energy Consumption.

The EE of cluster based CSS is determined by considering the four cases, described in section 5.2 in chapter 5. Apart from these four cases energy will be consumed during reporting of the cluster decision by CH to the base station since there are ‘L’ number of cluster and if the transmission power of reporting is α_r and reporting time is same as reporting time of SUs to report their decision to CH i.e. τ_r then energy consumption is given by

$$E_3(\tau_r) = L\alpha_r\tau_r. \tag{6.4}$$

The total energy consumption $\mathbb{E}$ of cluster based CSS can be determined by considering equations (5.5), (5.6), and (6.4)

$$\mathbb{E}(\tau) = ML\,\tau\,T\theta_s + (M-1)L\,\tau_r\,\theta_t + \mathrm{L}\alpha_r\tau_r + \Big(P_0\left(1 - Q_f(\tau)\right) + P_1\left(1 - Q_d(\tau)\right)\Big)\tau_d\,\theta_t, \tag{6.5}$$

where θ_s and θ_t are sensing power and transmission power of each SU respectively, τ_d is the data transmission time, P_1 is the probability of the PU being busy and P_0 is the probability of the PU being idle.

6.2.2 Throughput

Since data is successfully transmitted in the fourth stage, throughput ($\mathbb{R}$) is given by equation (5.8) of chapter 5.

$$\mathbb{R}(\tau) = P_0\left(1 - Q_f\right)\tau_d\,C_0, \tag{6.6}$$

where C_0 is the channel capacity over the period τ_d , it can be calculated as $C_0 = B\log_2\left(1 + \frac{\alpha_r}{\Gamma}\right)$, where B is the channel bandwidth and Γ is the noise power over B.

6.2.3 Energy Efficiency

The EE (ξ) is defined as the rate of successful data transmission per unit energy consumed which can be given by

$$\xi(\tau) = \frac{\mathbb{R}(\tau)}{\mathbb{E}(\tau)}. \tag{6.7}$$

The number of clusters (L) and number of users in the cluster (M) are integer numbers, which means $\xi(\tau)$ is not a continuous function of L and M. So it is not feasible to derive an analytical solution for optimum L and M. So we propose an iterative algorithm which finds the optimum number of clusters (L_{max}) and number of users in the cluster (M_{max}) that maximizes $\xi(\tau)$ for fixed number of total users $N = L \times M$.

Table 6:1 Proposed Iterative Algorithm to find optimum cluster and number of users in a cluster

Initialize T, N, f_s, θ_s , θ_t , τ_r , α_r, $\bar{P}_d$, N, m_{max}

Let m_0 =1 and l_0=$\lfloor\frac{N}{m_0}\rfloor$

1. while $m < m_{max}$
2. Compute $\xi(\tau, m_0, l_0)$
3. $m = m_0$ +1
4. l =$\lfloor\frac{N}{m}\rfloor$
5. If $\xi(\tau, m_0, l_0) < \xi(\tau, m, l)$ then
6. $m_0 = m$
7. $l_0 = l$
8. $else$
9. m_0 = m_0 +1
10. l_0=$\lfloor\frac{N}{m_0}\rfloor$
11. end if
12. end while
13. Return $M_{max} = m_0, L_{max} = l_0, \xi_{max}(\tau, M_{max}, L_{max})$

Here $\lfloor.\rfloor$ denotes floor function

The overall complexity of the given algorithm is $O\big(m_{max}log(ml)\big)$. Where m and l are number of SUs and number of clusters respectively and m_{max} is the maximum number of SUs in the CRN. Analytically if we take $m = 3$ and $l = 4$, than complexity comes out to be $O(14.3396)$

6.3 Numerical Results

The performance analysis of spectrum sensing is done assuming the perfect reporting channels between the fusion center and SUs. The number of clusters (L) are taken as 4 and within a cluster number of users (M) are equal to 3. According to IEEE 802.22 WRAN standard, the SNR for TV white space is around -18dB to -20dB. The other simulation parameters are taken as T= 50 ms, $\bar{P}$d = 0.9, f_s = 6MHz, $\theta_s = 0.1W$, $\theta_t = 0.5W, \alpha_r = 3W,$ ${\sigma_n}^2$ = 1, $\tau_r = 10\mu s$ P_0 = 0.75 and noise power (Γ), is computed according to method described in [108].

The energy consumed in transmitting l bit through distance d_i is [126]

$$E_t = l \times E_{elc} + l \times \epsilon_{fs}{d_i}^2, \tag{6.8}$$

where E_{elc} is the transmitter electronic energy and ϵ_{fs} is the energy needed to satisfy sensitivity level of the receiver. The parameter E_{elc} and ϵ_{fs} are set according to reference

[126], $'l'$ taken as 1. The Transmission and sensing power are determined by using equation 6.8. In Figure 6.2, the variation of false alarm probability has been investigated against normalized sensing time for different fusion rules.

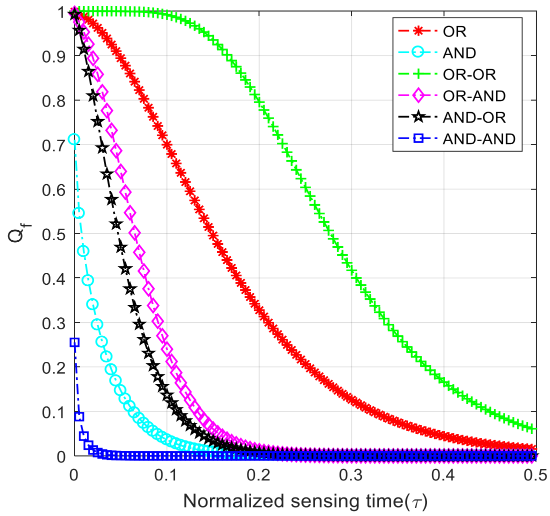

Figure 6.2 False alarm probability for different fusion rules at SNR=-20dB

It can be observed from Figure 6.2 that false alarm is minimum in case of AND-AND fusion and it is maximum for OR-OR fusion because in case of AND fusion the FC cannot predict the presence of PU until all the CR users give the decision of PU presence. On the other hand in OR fusion FC can predict PU presence when only single CR user gives the decision of the presence of PU so in OR fusion chances of false alarm is high compared to AND fusion.

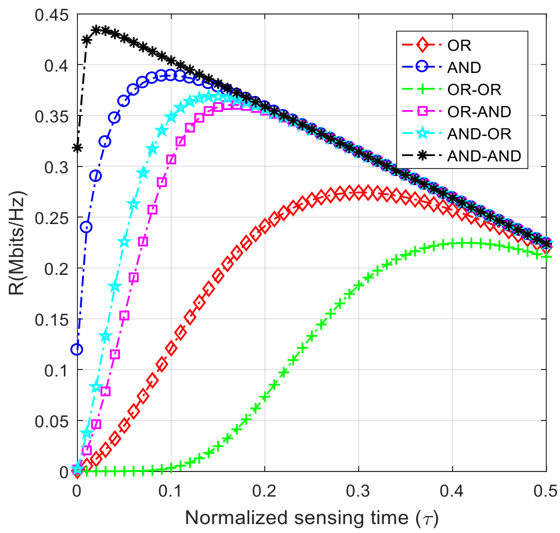

Figure 6.3 Throughput for different fusion rules at SNR=-20dB

Results published in the paper: "Optimised fusion rule in cluster-based energy-efficient CSS for cognitive radio networks." International Journal of Electronics (2018): 1-15. DOI: 10.1080/00207217.2018.1553248

In Figure 6.3 throughput ($\mathbb{R}$) is plotted against normalized sensing time (τ) for different fusion rules. Initially throughput increases with sensing time because SUs get large sensing time to identify the vacant spectrum. When sensing time further increases, data transmission time starts decreasing and thus there will be less time to send the data so throughput decreases. Figure 6.3 show that throughput is maximum for AND-AND fusion and minimum for OR-OR fusion because $\mathbb{R}$ is maximum when false alarm probability is minimum and for AND fusion, false alarm probability is minimum. High false alarm probability leads to loss of data as data transmitted by the CR users can interfere with the PU signal.

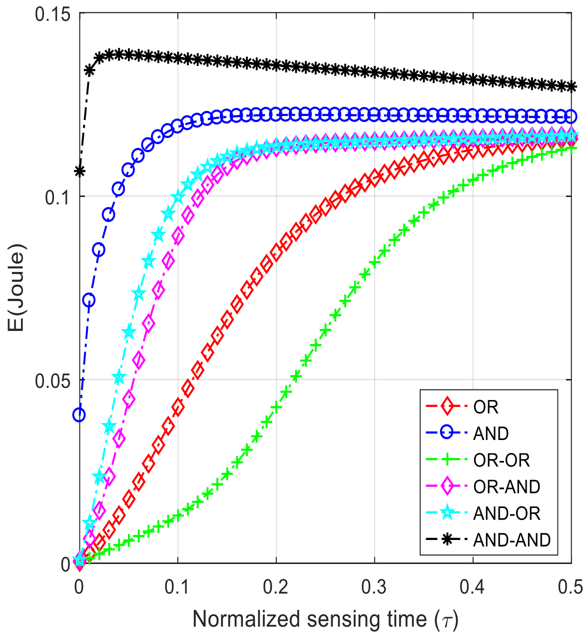

Figure 6.4 Energy consumption for different fusion rules at SNR= -20dB

Energy consumption ($\mathbb{E}$) against normalized sensing time (τ) for different fusion rules is plotted in Figure 6.4. It is observed from Figure 6.4 that $\mathbb{E}$ is maximum for AND-AND fusion and minimum for OR-OR fusion because AND fusion results in low detection probability and OR fusion results in high detection probability. Data transmission cannot takes place until empty spectrum is detected successfully which later results in energy consumption in transmission.

From Figure 6.3 and Figure 6.4 it can be analyzed that both energy consumption ($\mathbb{E}$) and throughput ($\mathbb{R}$) is maximum for AND-AND fusion and minimum for OR-OR fusion. Also, both $\mathbb{R}$ and $\mathbb{E}$ increases with sensing time and attains a maximum value and then the value of EE decreases. In the beginning, as sensing time increases, sensing performance improves and thus both $\mathbb{R}$ and $\mathbb{E}$ increases. But when sensing time is further increased, data transmission

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time decreases and thus both ℝ and 𝔼 decreases. In order to maximize the EE which is the ratio of throughput and energy consumption, the throughput needs to be maximized and energy consumption needs to be minimized.

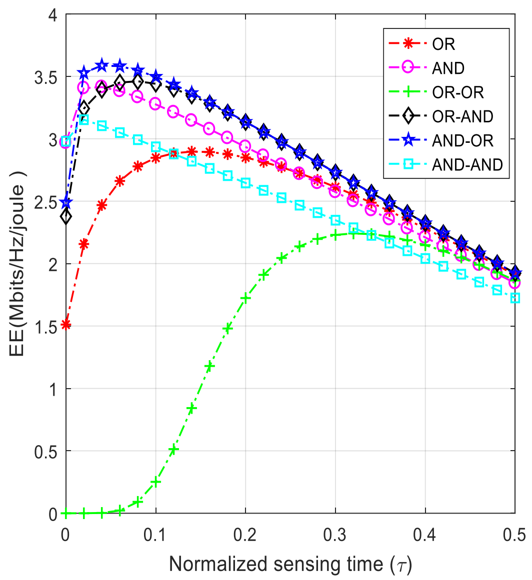

Figure 6.5 EE for different fusion rules at SNR=-20dB

In Figure 6.5, EE is plotted against normalized sensing time for different fusion rules. It is observed from Figure 6.5 that EE is maximum for AND-OR fusion and it is minimum for OR-OR fusion for sensing time less than 5ms. The maximum EE is 3.586 Mbits/Hz/joule at sensing time equal to 2ms.

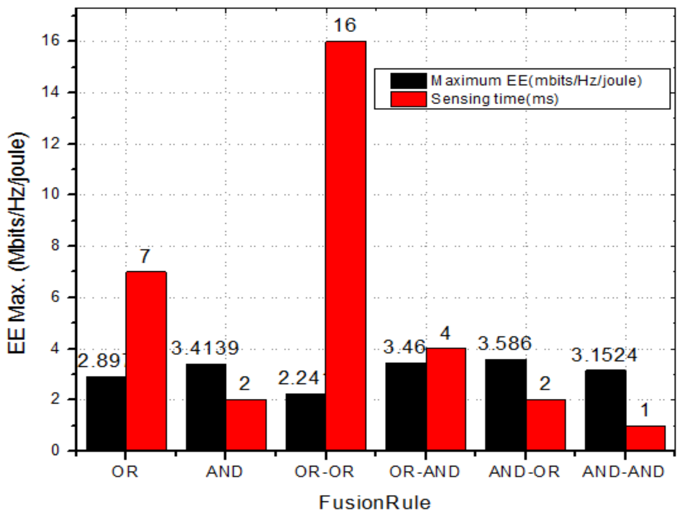

Figure 6.6 Performance comparison of fusion rules

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Figure 6.6, Performance of different fusion rules are compared. It is observed from Figure 6.6 that maximum EE is achieved for AND-OR fusion. It is 3.65% more than OR-AND fusion and 60% more than OR-OR fusion which attains minimum EE out of all fusion rules. It is also observed that OR-OR fusion required maximum sensing time to attain maximum EE which is 16ms.

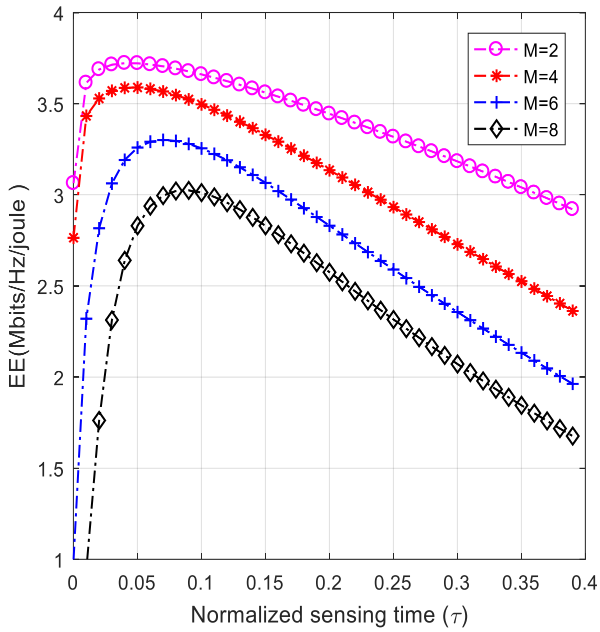

Figure 6.7 EE for AND-OR fusion rules at SNR = -20dB when number of clusters (L) are fixed = 3 and number of users (M) in the cluster varied

In Figure 6.7 EE is plotted against normalized sensing time for AND-OR fusion at SNR= -20dB when number of clusters (L) are fixed =3 and number of users (M) in the cluster are varied from 2 to 8. It is observed from Figure 6.7 that as the number of users in the cluster increases, Maximum value of EE decreases because as the number of user increases, energy consumption and sensing time also increases which further reduces the data transmission time. Figure 6.8 justifies the proposed algorithm given in table 6.1. In Figure 6.8 EE is plotted against normalized sensing time for AND-OR fusion when total number of users (L× M) are fixed = 12 and both, number of clusters (L) and number of users (M) in the cluster are varied. It is observed from Figure 8 that EE is maximum when number of clusters (L) = 4 and number of users in the cluster (M) =3, clearly it shows that clustering of users maximizes the value of EE and there is the optimum number of clusters and number of users for which EE is maximum. The maximum EE is 3.69 Mbits/Hz/joule at sensing time 1.5ms.

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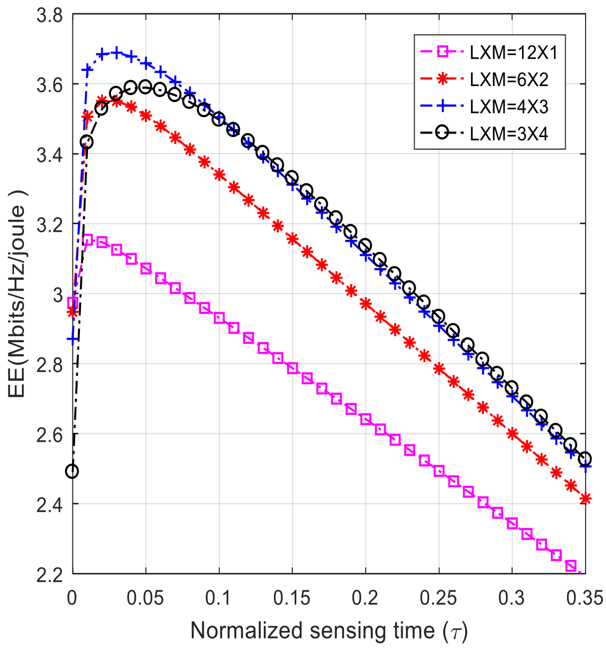

Figure 6.8 EE for AND-OR fusion rules at SNR=-20dB when total number of users (L× M) are fixed = 12 and both number of clusters (L) and number of users (M) in the cluster are varied.

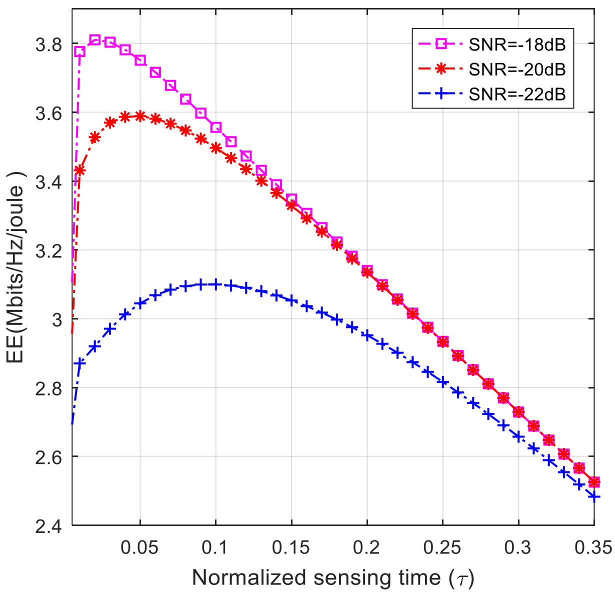

Figure 6.9 EE for AND-OR fusion rules at different SNR

Figure 6.9 show the impact of SNR on EE when AND-OR fusion is used. It is observed from Figure 6.9 that as SNR decreases, maximum EE decreases and sensing time increases because when radio conditions become worse, the CR user requires more sensing time to achieve the target detection probability.

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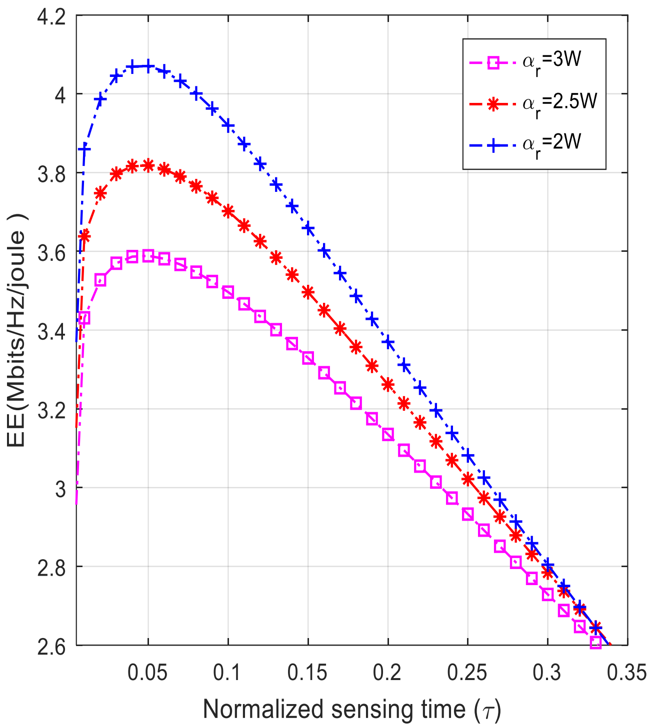

Figure 6.10 EE for AND-OR fusion rules at different transmission powers

Figure 6.10 show the impact of transmission power on EE when AND-OR fusion is used. It is observed from Figure 6.10 that as transmission power decreases, maximum EE increases but sensing time remains same for maximum EE because of energy consumption increases when transmission power increases which tend to decrease the maximum EE.

6.4 Conclusion

In this chapter performance of cluster-based centralized CSS is presented on the basis of EE metric. Centralised CSS has been discussed with two fusion rules and cluster-based CSS (CBCSS) is discussed with four different fusion rules. The results show that for CBCSS, AND-OR fusion outperforms the other fusion rules to maximize the EE. It is also found that there is an optimum number of clusters and number of users in the clusters at which EE is maximum. The maximum EE is 3.69 Mbits/Hz/joule at sensing time 1.5ms when number of clusters are 4 and number of users in the cluster are 3. For total number of users equals to 12, it is found that EE increases 16.35% when the number of clusters increases from 1 to 4. Further, the impact of SNR and transmission energy on EE has also been investigated. The difference of the proposed work with previous work by Wu *et al.*, 2017 [127] is given in table 6.2.

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Table 6:2 Difference of proposed work with previous work

Parameter	**Work [127]**	**Proposed work**
Frame duration	50 ms	50 ms
Sensing power	20 mW	100 mW
Transmission power	20 mW	500 mW
Total number of sensing users	55	12
Fusion Rule	k-out of –N (k = 5)	AND-OR fusion
Maximum Throughput	2.47X10^4 bits/Hz	44X10^4 bits/Hz
Maximum EE	17.15Mbits/Hz/Joule	3.586 Mbits/Hz/joule
Optimum sensing Time	6.5ms	2 ms

It is clear form table 6.2 that proposed work gives better throughput at lower sensing duration. Maximum EE is better in [127] because in [127]sensing and transmission power is assumed low compared to the proposed work in this chapter. Hence, there will be lower energy consumption in [127]. So overall EE is lower in the proposed work compared to previous work.

In this chapter PU traffic is not considered. During sensing, PU traffic must be considered since during transmission time PU might recommence transmitting. Also the reporting channel is considered perfect.

In the next chapter EE is maximized for the CBCSS, taking AND-OR fusion under consideration. The impact of joint transmission power and sensing time on this CBCSS is discussed for imperfect reporting channel considering PU traffic.

CHAPTER 7: JOINT SENSING TIME AND TRANSMISSION POWER OPTIMIZATION FOR ENERGY EFFICIENT CB-CSS

Cooperative spectrum sensing (CSS) is an efficient spectrum sensing technique to improve the sensing accuracy in CR. However, it brings extra collaborative sensing overhead due to mutual exchange of large information among CR users. In CSS, the number of cooperative users, fusion rule, transmission power and sensing time affects the EE of the CSS. In this chapter a cluster based CSS is presented with four fusion rules. Optimized fusion rule is determined that maximizes the EE. For the proposed CSS, joint optimal sensing time and transmission power of energy efficient CSS is determined. The joint optimization design problem is formulated as function of sensing time and transmission power subjected to PU protection constraints. An iterative algorithm is proposed to determine joint optimal sensing time and transmission power that maximizes the EE of CSS.

7.1 System model

The system model for the problem is same as described in section 5.1 of chapter 5. During sensing, PU traffic must be considered since during transmission time τ_d , PU might recommence transmitting. It can lead to unwanted interference to the PU. Therefore, PU traffic must be considered. If idle and busy states of PU is exponentially distributed with mean values a_0 and a_1 respectively then density function for idle and busy states are given by:

$$f_0(t) = \frac{1}{a_0}\exp\frac{-t}{a_0} \quad \text{and} \quad f_1(t) = \frac{1}{a_1}\exp\frac{-t}{a_1} \qquad t \geq 0, \tag{7.1}$$

where $f_0(t)$ and $f_1(t)$ are the probability density functions of the idle and busy PU states respectively.

If P_0 and P_1 are the probabilities of PU being idle and busy respectively and P_f and P_d are the probabilities of false alarm and detection respectively. SU can start transmitting data if it detects the absence of PU successfully with probability $P_0(1 - P_f)$ or it fails in detecting presence of PU correctly with probability $P_1(1 - P_d)$ and it will sleep if it detects presence of PU successfully with probability P_1P_d or falsely detects the absence with probability P_0P_f. The probability that PU might reappear when SU transmits the data with duration τ_d can be determined by [94].

$$P_1(\tau_d) = \int_{\tau=0}^{\tau_d} f_0(t)\, dt = 1 - \exp(-\tau_d/a_0). \quad (7.2)$$

The false alarm and detection probability at j[th] CR can be determined using equation (5.1) and (5.2) respectively. If P_e is the bit error rate between SU and FC and a common threshold ε is used for all CR users then ${P_f}^j = P_f$ and ${P_d}^j = P_d$. False alarm and detection probability for this imperfect reporting can be determined by

$$P_{f1} = P_f(1 - P_e) + \left(1 - P_f\right)P_e \quad (7.3)$$

$$P_{d1} = P_d(1 - P_e) + (1 - P_d)P_e. \quad (7.4)$$

For fixed number of CR users and target false alarm probability when base station uses k out of N fusion rule, the overall detection and false alarm probabilities are given by

$$Q_f(\tau_s) = \sum_{i=k}^{N} \binom{N}{j} {P_{f1}}^i \left(1 - P_{f1}\right)^{N-i} \quad (7.5)$$

$$Q_d(\tau_s) = \sum_{i=k}^{N} \binom{N}{j} {P_{d1}}^i (1 - P_{d1})^{N-i}, \quad (7.6)$$

where k = 1 is OR fusion rule and k = N is AND fusion rule.

7.1.1 Cluster based CSS:

The structure of cluster based CSS is same as given in Figure 6.1 of chapter 6. It is assumed that there are L number of clusters and in each cluster there are M SUs. So the total number of CR users in the system is N = M×L. All the CR users are assumed to be grouped into small clusters. For each cluster, a SU is set as cluster head (CH). There are four fusion possible for this cluster based CSS, OR-OR fusion, OR-AND fusion, AND-OR fusion & AND-AND fusion. The probability of false alarm, detection probability and miss detection probability of these four fusion rules is given in section 4.2 of chapter 4.

7.2 Problem Formulation:

The aim is to maximize the EE by jointly optimizing the sensing time and transmission power subjected to PU interference constraints. The design problem can be setup by first considering the total energy consumption $\mathbb{E}(\tau_s, \theta_t)$, which is determined from equation (6.5)

$$\mathbb{E}(\tau_s, \theta_t) = N\,\tau_s\,\theta_s + N\,\tau_r\,\theta_t + \left(P_0\left(1 - Q_f(\tau_s)\right) + P_1\left(1 - Q_d(\tau_s)\right)\right)\tau_d\theta_t, \quad (7.7)$$

where $N = M \times L$ is total number of users, M = number of users in cluster and L = total number of clusters, τ_s = sensing time, τ_r = reporting time, τ_d= data transmission time, θ_s= sensing power, θ_t= transmission power, Q_f= global false alarm probability, Q_d =gloabal detection probability, P_0= probability of PU being idle and P_1= probability of PU being busy.

The average throughput $\mathbb{R}(\tau_s, \theta_t)$ is determined as

$$\mathbb{R}(\tau_s, \theta_t) = P_0\, \tau_d C\big(1 - Q_f\big)\big(1 - P_1(\tau_d)\big). \tag{7.8}$$

The design parameters θ_t and τ_s have the direct impact on the EE. The EE (ξ) is defined as the rate of successful data transmission per unit energy consume which can be given by

$$\xi(\tau_s, \theta_t) = \frac{\mathbb{R}(\tau_s,\theta_t)}{\mathbb{E}(\tau_s,\theta_t)}. \tag{7.9}$$

The design problem aims to maximize EE by varying the transmission power and sensing time. Mathematically the optimization problem can be stated as

$$\begin{aligned} &\text{Find:} \quad (\tau_{s0}, \theta_{t0}) \\ &\text{Max.:} \quad \xi(\tau_s, \theta_t) \\ &\text{S.t.:} \quad T \geq \tau_s \geq 0,\ \theta_{max} \geq \theta_t \geq \theta_{min}, Q_d \geq \delta,\ P_1(\tau_d) \leq a_i \end{aligned} \tag{7.10}$$

where τ_{s0}, θ_{t0} are the optimum values of sensing time and transmission power respectively, θ_{max} and θ_{min} are maximum and minimum transmission powers, δ is the target probability of detection and a_i is the maximum limit of interference level allowed to the PU.

7.3 Proposed Algorithm

For reporting time $\tau_r \ll T$, normalized sensing time is defined as $\tau = \frac{\tau_s}{T}$ and data transmission time $\tau_d = (1-\tau)T$. This assumption is helpful in reducing the complexity of the optimizing problem. The detection probability constraint of the optimization problem can be satisfied by determining the probability of false alarm from equation 6.3 as:

$$P_f(\tau) = Q\big(\sqrt{2\gamma_1 + 1}\ Q^{-1}(\bar{P}_d) + \gamma\sqrt{\tau f_s \mathrm{T}}\big), \tag{7.11}$$

$\bar{P}_d$ is the target detection probability of individual CR. If $\dot{P}_f$ and $\ddot{P}_f$ represents first and second partial derivatives of P_f then it can be proved [91] that $\dot{P}_f(\tau) < 0$ and $\ddot{P}_f(\tau) > 0$ hence $P_f(\tau)$ is a convex function of τ. However, τ should be limited to be within some interval $[\tau_{min}, \tau_{max}]$. The upper bound can be determined by applying constraint in (7.10) $\tau_{max} = 1 + \frac{a_0}{T}(1 - a_i)$ and lower bound can be calculated by letting $P_f(\tau) < 0.5$ therefore from (7.11), $\tau_{min} = \left(\frac{\sqrt{2\gamma+1}\, Q^{-1}(\bar{p}_d)}{\gamma_1\sqrt{Tf_s}}\right)^2$ also IEEE802.22 standard constraint in (7.10) grants that $P_d(\tau) = \bar{P}_d$ at any radio conditions. Now energy consumption $\widehat{\mathbb{E}}$ can be determined in terms of τ and θ_t as follows.

$$\widehat{\mathbb{E}}(\tau, \theta_t) = N\,\tau\,T\,\theta_s + \left(P_0\left(1 - Q_f(\tau)\right) + P_1\left(1 - Q_d(\tau)\right)\right)(1-\tau)T\theta_t, \tag{7.12}$$

In addition, the throughput can also be determined in terms of τ and θ_t as follows:

$$\widehat{\mathbb{R}}(\tau, \theta_t) = P_0(1-\tau)T \times \left(1 - Q_f(\tau)\right) \times exp\left(\frac{-\left((1-\tau)T\right)}{a_0}\right) \times \beta \log_2\left(1 + \frac{\theta_t}{\Gamma}\right). \tag{7.13}$$

The approximated EE ($\hat{\xi}$) is computed as $\hat{\xi}(\tau, \theta_t) = \frac{\widehat{\mathbb{R}}(\tau,\theta_t)}{\widehat{\mathbb{E}}(\tau,\theta_t)}$ and optimization problem can be rewritten as

$$\begin{gathered} \text{Find: } (\tau_0, \theta_{t0}) \\ \text{Max.: } \hat{\xi}(\tau, \theta_t) \\ \text{S.t.: } \tau_{max} > \tau \geq \tau_{min},\ \theta_{max} \geq \theta_t \geq \theta_{min}, \end{gathered} \tag{7.14}$$

where τ_0, θ_{t0} are the optimum values of normalized sensing time and transmission power respectively. From (7.14), it is seen that number of constraints are minimized from four to two, which will make the proposed algorithm simple to implement.

Proposition 7.1: For a given value of sensing time, EE is maximum at optimal value of transmission power (i.e.θ_{t0}).

Proof: In equation (7.13) let $P_0(1-\tau)T \times \left(1 - Q_f\right) \times exp\left(\frac{-\left((1-\tau)T\right)}{a_0}\right)\beta = C_1$ and in equation (7.12) let $N\,\tau\,T\,\theta_s = C_2$ and $\left(P_0\left(1 - Q_f(\tau)\right) + P_1\left(1 - Q_d(\tau)\right)\right) \times (1-\tau)T = C_3$ then EE in equation (7.14) can be written as $\hat{\xi}(\tau, \theta_t) = \left(\frac{C_1\,\log_2\left(1+\frac{\theta_t}{\Gamma}\right)}{C_2 + C_3\theta_t}\right)$. To find the maximum value of EE, $\hat{\xi}(\tau, \theta_t)$ is partially differentiated w.r.t θ_t. Hence

$$\acute{\xi}(\tau, \theta_t) = \frac{\partial\hat{\xi}(\tau,\theta_t)}{\partial\theta_t} = \frac{\frac{\Gamma C_1(C_2 + C_3\theta_t)}{ln2(\Gamma+\theta_t)} - C_2C_1\,\log_2\left(1+\frac{\theta_t}{\Gamma}\right)}{(C_2 + C_3\theta_t)^2}, \tag{7.15}$$

From (7.15) it is difficult to find the optimal value of θ_t (i.e. θ_{t0}). However it can be confirmed from (7.15) that $\theta_{t0} \in (0, \infty)$.

Now there are 3 possible cases.

Case1: If $\acute{\xi}(\tau, \theta_{max}) = 0$ or $\acute{\xi}(\tau, \theta_{min}) = 0$, therefor $\theta_{t0} = \theta_{max}$ and $\theta_{t0} = \theta_{min}$ respectively

Case2: If $\acute{\xi}(\tau, \theta_{max}) < 0$ and $\acute{\xi}(\tau, \theta_{min}) > 0$, therefor $\theta_{t0} \in (\theta_{min}, \theta_{max})$

Case3: If $\acute{\xi}(\tau, \theta_{max}) > 0$ and $\acute{\xi}(\tau, \theta_{min}) > 0$, therefor $\theta_{t0} \notin (\theta_{min}, \theta_{max})$, which is impractical.

Proposition 7.2: For a given value of transmission power, there is an optimal sensing time, τ (i.e., τ_0) that maximizes the $\hat{\xi}(\tau, \theta_t)$ where $\tau_0 \in [\tau_{min}, \ \tau_{max}]$.

Proof: Proposition 7.2 is already proved in proposition 5.1 in chapter 5.

Table 7:1 Pseudo code for bisection Algorithm

Calculate a and b

1. **Procedure** bisection method (a,b,ϵ)
2. $c = \frac{a+b}{2}$
3. Compute derivative of $f(x)$ denoted as $\acute{f}(x)$
4. **While** $|a-b| \geq \epsilon$ and $\acute{f}(x) \neq 0$ **do**
5. **If** $\acute{f}(a) \times \acute{f}(c) < 0$ **then**
6. $b \leftarrow c$
7. **Else**
8. $a \leftarrow c$
9. $c \leftarrow \frac{a+b}{2}$
10. **Return** a or b or c

Since $\hat{\xi}(\tau, \theta_t)$ is a concave function of τ and θ_t we can use bisection method to determine optimal τ i.e. τ_0 and optimal θ_t i.e. θ_{t0} . The proposed algorithm jointly optimize sensing time (τ) and Transmission power (θ_t) to maximize EE (ξ). The results obtained from table 7.2 are further analysed in numerical results section.

Table 7:2 Proposed double bisection algorithm

Step 1: Inputs: N, a_0 , a_1, a_i, δ, T, τ_r , θ_s , f_s, θ_{max} , θ_{min} , P_0 , P_1, γ, ϵ

Step 2: Initialize: τ_{max} , τ_{min} , k=1

Step 3: Let $\theta_1 = \theta_{min}$

Step 4: Calculate $\tau_1 = bisect(\hat{\xi}(\tau, \theta_t), \tau_{max}, \tau_{min})$

Step 5: Let $\tau_{min} = \tau_1$ and $\theta_2 = \theta_{max}$

Step 6: Calculate $\tau_2 = bisect(\hat{\xi}(\tau, \theta_t), \tau_{max}, \tau_{min})$

Step 7: Let $\tau_{max} = \tau_2$

Step 8: While ($\left|\hat{\xi}(\tau_k, \theta_k)\right|$) - $\left|\hat{\xi}(\tau_{k+1}, \theta_{k+1})\right|$) $>$ ϵ **do**

Step 9: Update k

Step 10: $\theta_k = \frac{\theta_{min} + \theta_{max}}{2}$

Step 11: $\tau_k = bisect(\hat{\xi}(\tau, \theta_t), \tau_{max}, \tau_{min})$

Step 12: If $\hat{\xi}(\tau_k, \theta_k) < 0$ **then**

Step 13: $\theta_{max} = \theta_k$

Step 14: $\tau_{max} = \tau_k$

Step 15: else

Step 16: $\theta_{min} = \theta_k$

Step 17: $\tau_{max} = \tau_k$

Step 18: end if

Step 19: end while

Step 20: Return $\theta_{t0} = \theta_k$ and $\tau_0 = \tau_k$

7.4 Numerical Results

The simulation parameters are taken as N = 10, T = 50 ms, $\theta_{max} = 4W$, $\theta_{min} = 0.1W$, $\delta = 0.9$, $f_s = 6\text{MHz}$, $\theta_s = 0.2W$, $\sigma_n{}^2 = 1$, $\tau_r = 10\mu s$, $a_i = 0.1$, $a_0 = 0.6s$, $a_1 = 0.35s$, $P_0 = 0.5$ the noise power Γ is determined according to [108] number of clusters (L) = 4 and total number of users in a cluster (M) = 3.

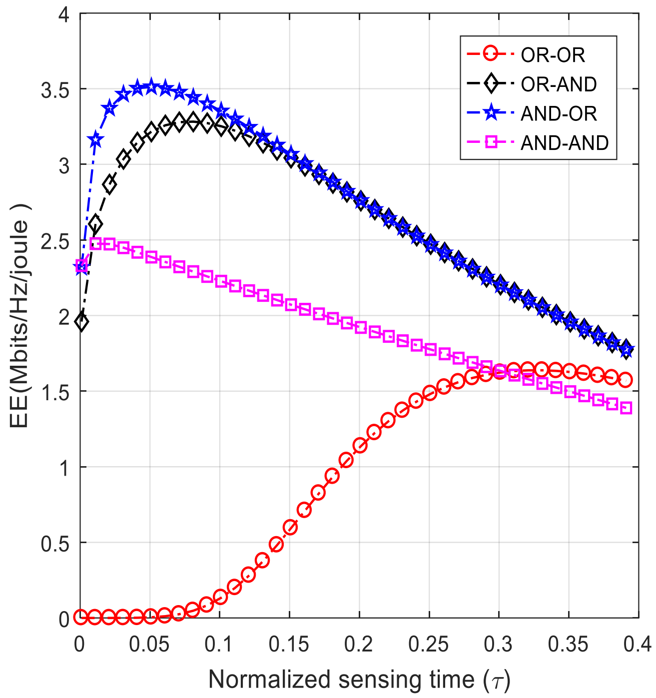

Figure 7.1 Energy Efficiency (ξ) vs. normalized sensing time (τ) at θ_t = 2W and SNR = -20dB for different fusion rules

In Figure 7.1 EE is plotted against normalized sensing time at transmission power equals to 2W and in Figure 7.2 EE is plotted against transmission power at normalized sensing time equals to 0.06. For both the plots, SNR is kept fixed at -20dB. It is observed form Figure 7.1 and 7.2 that EE is maximum for AND-OR fusion and minimum for OR-OR fusion with respect to both transmission power and normalized sensing time. In OR fusion, false alarm is high and detection probability is low but in AND fusion, detection probability is low but false alarm is high. High false alarm leads to low throughput and low energy consumption and low detection probability leads to high energy consumption. Both throughput and energy consumption affects the EE.

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For AND-OR fusion, SUs exchange sensing information and fuse with CH using AND fusion with high detection probability and low energy consumption and CHs fuse its information with OR fusion with high throughput. So the overall EE is high for AND-OR fusion.

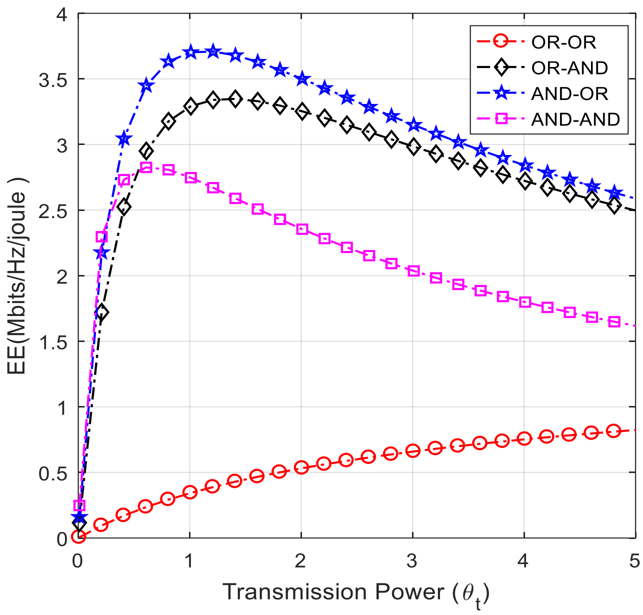

Figure 7.2 Energy Efficiency (ξ) vs. transmission power (θ_t) at τ = 0.06 and SNR = -20dB for different fusion rule

In Figure 7.1, maximum EE (ξ_{max}) = 3.512 Mbits/Hz/joule at normalized sensing time $\tau_0 = 0.051$. Since EE is maximum for AND-OR fusion, hence for further analysis AND-OR rule is used for fusion.

A 3-D plot of EE and its contour are demonstrated in Figure 7.3 and 7.4, respectively. Figure 7.3 shows variation of EE with normalized sensing time (τ) and transmission power (θ_t) at SNR = -20dB for AND-OR fusion. It shows that EE is a concave function of both sensing time and transmission power and there is a unique optimum point i.e. joint optimum θ_{t0} and τ_0 that maximizes the EE.

In Figure 7.4 contour of Figure 7.3 is drawn for better understanding of optimum values. The nature of graph in Figure 7.3 and 7.4 is further explained in Figure 7.7 and Figure 7.8. Quantitatively, $\theta_{t0} = 1.11W$, $\tau_0 = 0.046$, and ξ_{max} = 3.735 Mbits/Hz/joule when SNR (γ) = -20dB. From Figure 7.3 the optimum θ_{t0} and τ_0 are same as obtained from algorithm in Table 7.2. This verifies that proposed algorithm can be successfully used to obtain both the optimum sensing time and fusion rule threshold.

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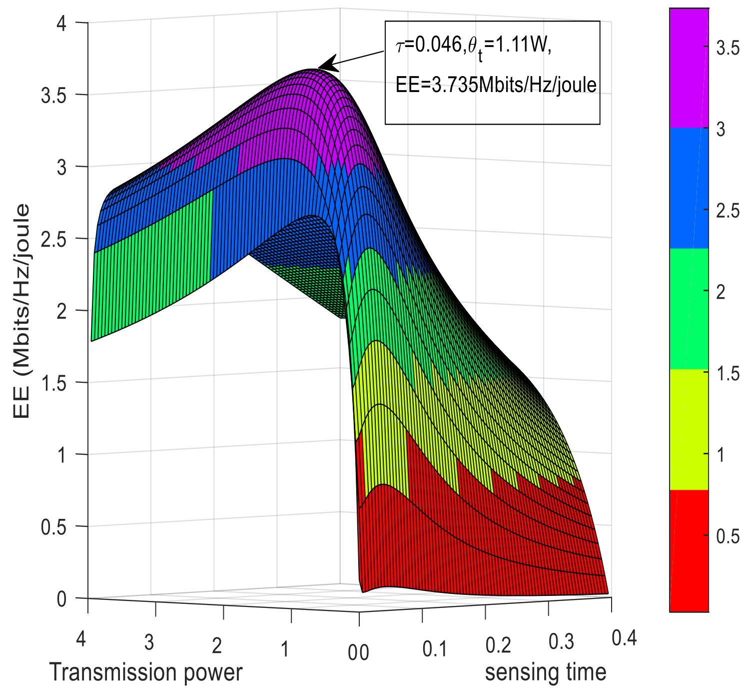

Figure 7.3 Energy Efficiency (ξ´) vs. normalized sensing time (τ) and transmission power (θ_t) at SNR = -20dB for AND-OR fusion

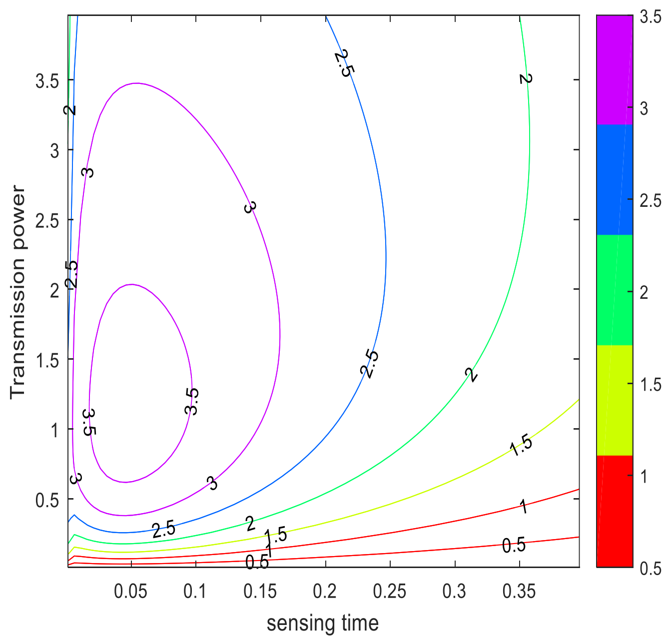

Figure 7.4 Contour of plot in Figure 7.3

In Figure 7.5 EE is plotted against number of users in a cluster for AND-OR fusion while total number of clusters are varied and SNR = -20dB. Figure 7.5 is plotted at optimum sensing time and transmission power.

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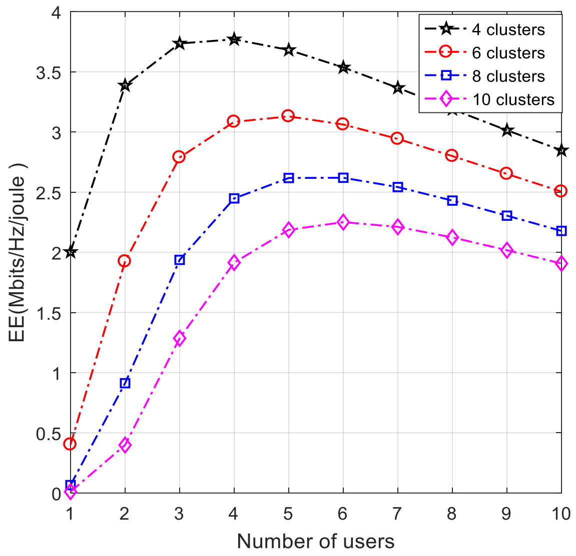

Figure 7.5 Energy Efficiency (ξ) vs. number of users in a cluster at optimum point (θ_{t0} ,τ_0)

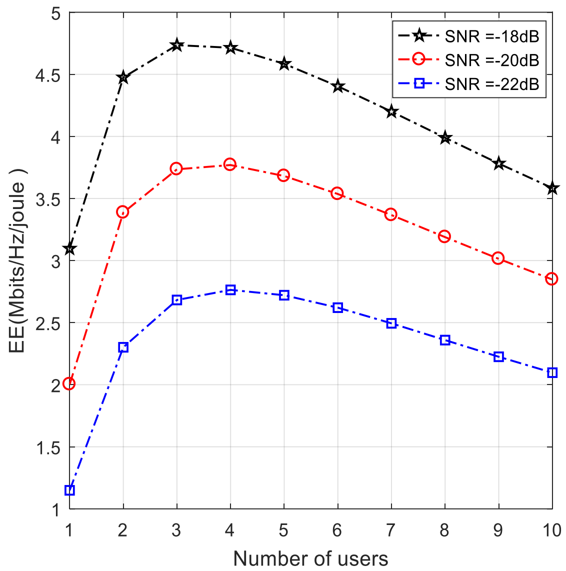

Figure 7.6 Energy Efficiency (ξ) vs. number of users in a cluster at (θ_{t0} = 1.11W, τ_0 = 0.046) for different SNR

It is observed from Figure 7.5 that initially as number of users increases, EE also increases because false alarm gets reduced when number of users are more. Low false alarm leads to high throughput. However, if number of users further increases, there will be more energy consumption due to large overhead hence, EE decreases.

In Figure 7.6 EE is plotted against number of users in a cluster for AND-OR fusion while SNR is varied and number of cluster is 4. Figure 7.6 is plotted at $\theta_{t0} = 1.11W, \tau_0 = 0.046$. The nature of the graph in Figure 7.6 is similar to Figure 7.5.

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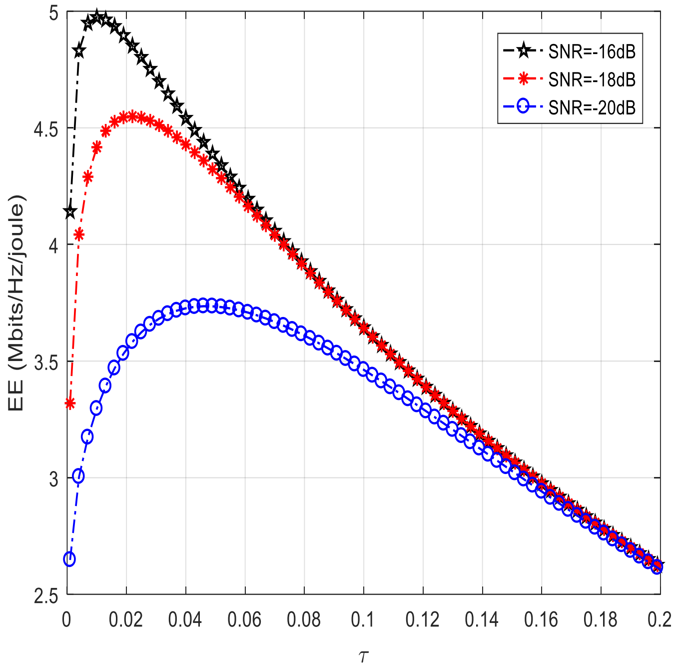

Figure 7.7 Energy Efficiency ($\hat{\xi}$) vs. normalized sensing time (τ) at θ_t = 1.11 W for different SNR

In Figure 7.7, EE ($\hat{\xi}$) is plotted against normalized sensing time (τ) for different SNR. In Figure 7.7 detector threshold (ε) is fixed for target detection probability ($\bar{P}_d$) = 0.9 and transmission power (θ_t) is fixed at 1.11W. EE is concave function of τ because at lower values of τ, data transmission time is high and at higher values of τ, data transmission time is low. It is observed from Figure 7.7 that optimization of sensing time is important as EE is maximum at optimum sensing time (τ_0), Maximum EE = 4.974 Mbits/Hz/joule at $\tau = 0.01$ for SNR = -16dB and at SNR = -20dB, Maximum EE = 3.735 Mbits/Hz/joule at $\tau = 0.046$. It is also observed in Figure 7.7 that as SNR decreases, EE also decreases because there will be more power consumption in worst radio condition.

In Figure 7.8 EE ($\hat{\xi}$) is plotted against transmission power (θ_t) at τ = 0.046 for different SNR. In Figure 7.8 initially, when θ_t is increased, the EE increases, this means the larger energies are consumed during transmission stage but transmission data volume also increases. However, when θ_t further increases, the EE decreases as energy consumption overcomes the throughput of the system. It is observed that maximum EE = 4.443 Mbits/Hz/joule at $\theta_t = 0.81W$ for SNR = -18dB.

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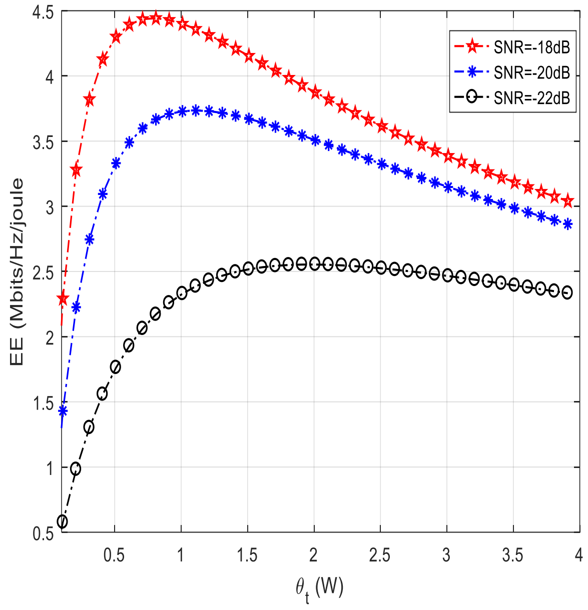

Figure 7.8 Energy Efficiency ($\hat{\xi}$) vs. transmission power (θ_t) at τ = 0.046 for different SNR

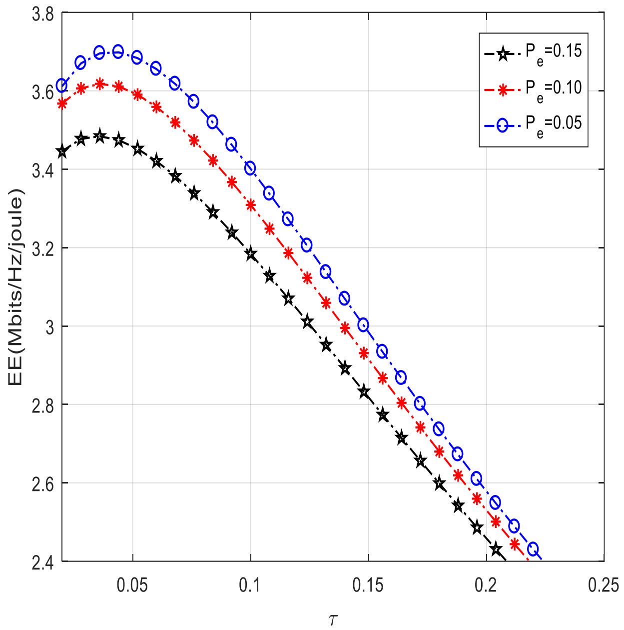

Figure 7.9 Energy Efficiency ($\hat{\xi}$) vs. normalized sensing time (τ) at θ_t = 1.11 W for different error probability

In Figure 7.9 EE ($\hat{\xi}$) is plotted against normalized sensing time (τ) at $\theta_t = 1.11\ W$ for different error probability. The sensing channel between SU and PU is assumed imperfect with probability of error P_e.

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The impact of error probability on EE is shown in Figure 7.9. High error probability can cause miss detection or false alarm, which can lead to decrement in EE. It can be observed from Figure 8 that for $P_e = 0.05$, EE is maximum and for $P_e = 0.15$ it is minimum. Maximum EE = 3.698Mbits/Hz/joule at $\tau = 0.044$ for $P_e = 0.05$.

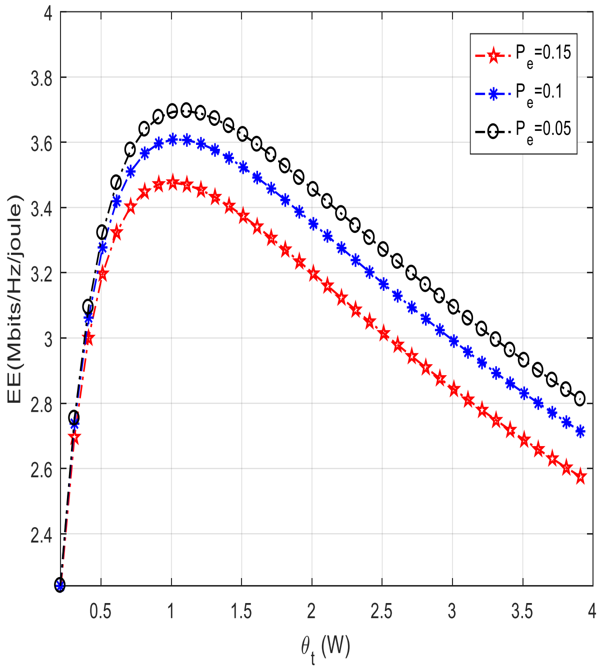

Figure 7.10 Energy Efficiency (ξ) vs. transmission power (θ_t) at τ = 0.046 for different error probability

In Figure 7.10, EE is plotted against transmission power (θ_t) at τ = 0.046 for different error probability. The results observed from Figure 7.10 shows the same trend as in Figure 7.9. As the error probability increases, EE decreases. Maximum EE =3.696 Mbits/Hz/joule at $\theta_t = 1.11\ W$ for $P_e = 0.05$.

In Figure 7.11 False alarm probability (Q_f) is plotted against normalized sensing time (τ) at optimum transmission power (θ_t). In Figure 7.11, (τ_1, θ_{t1}), (τ_2, θ_{t2}) and (τ_3, θ_{t3}) represents the optimum points at SNR = -18, -20 and -22 dB respectively. It is observed that none of the optimum point satisfies the target false alarm probability of 0.1. The optimum point can meet the target false alarm by increasing the transmission power (θ_t) but it leads to more energy consumption and minimizing the EE.

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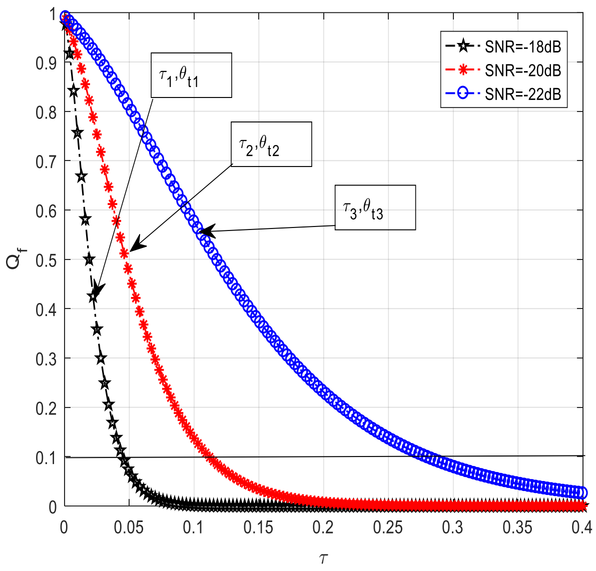

Figure 7.11 False alarm probability (Q_f) vs. normalized sensing time (τ) at optimum transmission power (θ_t)

To achieve the target value of false alarm, target detection probability may be reduced. In Figure 7.12 False alarm probability (Q_f) is plotted against normalized sensing time (τ) at different target detection probability.

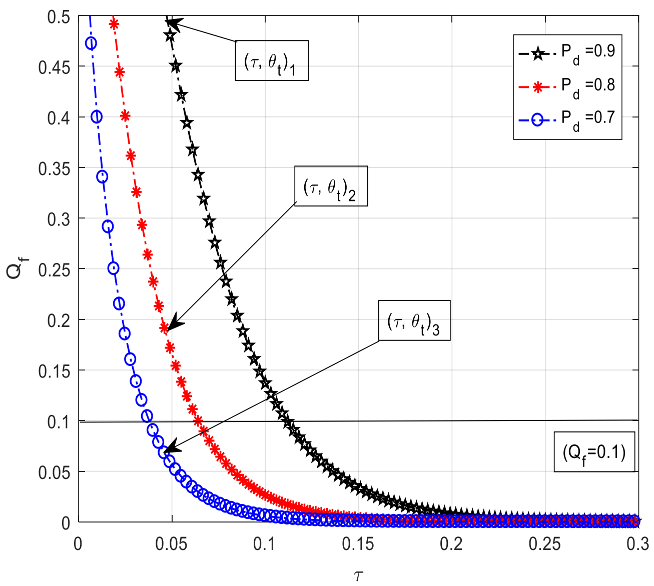

Figure 7.12 False alarm probability (Q_f) vs. normalized sensing time (τ) for different P_d at SNR = -20 dB

Lowering the value of target detection can satisfy the target false alarm probability at the same optimum point. In Figure 7.12 (τ, θ_t) represents the optimum point at SNR= -20dB. It is

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observed that at $\bar{P}_d$ = 0.7, false alarm value meets the target false alarm value of 0.1. Lowering the value of $\bar{P}_d$ can affect the overall EE since it will incur more energy consumption because data transmission time will increase.

7.5 Conclusion

The effect of varying the sensing time and transmission power on EE has been investigated for cluster based CSS. The investigations have shown that for AND-OR fusion, EE is maximum. To further determine the joint design parameters (i.e., transmission power and sensing time) that maximize the EE, a single iterative algorithm has been proposed. Quantitatively optimum sensing duration $(\tau_s) = 2.3\,ms$ and transmission power $(\theta_{t0}) = 1.11W$ at SNR = -20dB. Maximum EE at optimal point is (ξmax) = 3.735 Mbits/Hz/Joule. The analysis and formulation of design problem has been provided. The difference between proposed work and the work by **Awin *et al.*, 2016** [128] is given in table 7.3.

Table 7:3 Summary of differences with previous work

Parameters	**Previous work [128]**	**proposed work**
Joint optimized parameters	Sensing time and number of users	Sensing time, and transmission power
Intra cluster fusion	k out of N	AND, OR
Inter cluster fusion	-No fusion-	AND, OR
Iterative algorithm	Single bisection	Double bisection
Practical sensing channel	No	Yes
Analytical proof	sensing time	Both sensing time, and transmission power
Frame duration	150ms	50ms
Maximum EE	219bits/Hz/Joule	3.735 Mbits/Hz/Joule
Sensing time at maximum EE	11.25ms	2.3ms

The system model of [128] is based on a single cluster with 'N' number of users. Each CR user forwards its decision to the cluster head (CH) which combines the observations using k out of N rule. Therefore, only intra cluster fusion takes place and optimum number of users which maximize the EE is determined. There is no inter cluster fusion takes place.

DISSERTATION CONCLUSION AND FUTURE WORK

In this dissertation, detection and Energy Efficiency performance of CSS has been investigated and a cluster based CSS (CBCSS) scheme with different fusion rule is proposed.

Detection accuracy of cluster based CSS is investigated over Rayleigh, Rician and Nakagami fading channels. For this investigation energy detection method is used for local sensing. Hard fusion techniques like AND fusion rule and OR fusion rule are used for centralised CSS without clustering and for cluster based CSS four fusion schemes OR-OR, OR-AND, AND-OR , AND-AND are proposed. The detection performance of CBCSS is further improved by using different diversity combining techniques. In the second part EE performance of non-cluster based CSS and CBCSS is discussed. The effect of fusion rule threshold, sensing time, transmission power and number of SUs on EE is investigated. Iterative algorithms have been proposed which finds the optimum parameters for CBCSS and non-cluster based CSS. The achieved research results are summarized below.

Detection performance of centralised CSS and CBCSS is compared. It is found that for false alarm probability = 0.1, P_d = 0.79, 0.82, 0.83 for CBCSS, OR-OR fusion over Rayleigh, Rician and Nakagami fading channels respectively and P_d = 0.55, 0.58, 0.58 for Centralised CSS, OR fusion over Rayleigh, Rician and Nakagami fading channels respectively. Further, maximum ratio combining (MRC) and square law selection (SLS) diversity methods are used to improve the detection probability. It is found that for false alarm probability = 0.01, P_d = 0.76, 0.91, 0.99 for no diversity, SLS diversity and MRC diversity respectively. The investigation is done over Nakagami fading with number of diversity branch equals to two.

In the second part of the thesis, EE performance of CSS is discussed. Effect of varying the sensing time and fusion rule threshold on EE is investigated. The investigations have shown that there is an optimal value of fusion rule threshold and sensing time at which the EE is maximum. Quantitatively optimum sensing duration (τ_{s0}) = 0.841ms and fusion rule threshold (k_0) = 4 at SNR = -18dB. Maximum EE at optimal point is (ξ_{max}) = 3.15 Mbits/Hz/Joule. The analysis and formulation of design problem is provided. To determine the joint design parameters (i.e. fusion rule threshold and sensing time) that maximize the EE, a single iterative algorithm has been proposed. Results show that proposed work satisfy the detection accuracy metric.

EE performance of cluster-based CSS (CBCSS) is discussed with four different fusion rules. The results show that for CBCSS, AND-OR fusion outperforms the other fusion rules to maximize the EE. It is also found that there is an optimum number of clusters and number of users in the clusters at which EE is maximum. The maximum EE is 3.69 Mbits/Hz/joule at sensing time 1.5ms when number of clusters are 4 and number of users in the cluster are 3. For total number of users equals to 12, It is found that EE increases 16.35% when the number of clusters increases from 1 to 4.

After evaluating the EE, based on fusion rule, number of CR users and sensing time, the effect of joint varying the sensing time and transmission power on EE is investigated for CBCSS. The investigations have shown that for AND-OR fusion, EE is maximum. To further determine the joint design parameters (i.e., transmission power and sensing time) that maximize the EE, a single iterative algorithm is proposed. Quantitatively optimum sensing duration $(\tau_s) = 2.3\ ms$ and transmission power $(\theta_{t0}) = 1.11W$ at SNR = -20dB. Maximum EE at optimal point is $(\xi_{\max})$ = 3.735 Mbits/Hz/Joule.

8.1 Future Scope

- The impact of mobility of CRs on the detection performance in above algorithms is a valid point for future research. Furthermore, the impact of joint channel estimation and equalization on the detection performance of a moving CR can be investigated.
- The performance of CSS needs to be investigated over composite fading/shadowing channels.
- While we mainly discussed the detection accuracy using closed-form expressions for the probability of detection and the probability of false alarm as performance measures, closed-form expressions can also be derived for the outage probability, co-channel interference, and channel capacity to investigate how these metrics are affected by the fading/shadowing environment.
- Designing energy detector with adaptive sensing window size in order to improve spectrum efficiency of a single CR is very interesting research point. Markov process can be employed to predict the PU status in next sensing step. The principle of double threshold can also be employed to increase EE of the system.
- In this work, SUs are assumed to be distributed in a homogeneous manner. In practical environments, it is usual that the SUs have heterogeneity in spatial user distribution. In future work heterogeneous distributions of SUs may be considered.

- Practical implementations of all proposed algorithms using GNU radio software platform to investigate the detection performance of the proposed algorithms in real time world can be considered.

APPENDIX A

PROOF THAT $P_d(\tau_s)$ IS A CONCAVE FUNCTION OF τ_s :

From equation (5.13) $P_d(\tau_s) = Q\left(\frac{1}{\sqrt{2\gamma+1}}\left(Q^{-1}(\bar{P}_f) - \sqrt{\tau_s f_s}\,\gamma\right)\right)$

Let $\frac{Q^{-1}(\bar{P}_f)}{\sqrt{2\gamma+1}} = A$ and $\frac{\gamma\sqrt{f_s}}{\sqrt{2\gamma+1}} = B$

$$P_d(\tau_s) = Q\left(A - B\sqrt{\tau_s}\right) \approx \frac{1}{\left(A-B\sqrt{\tau_s}\right)\sqrt{2\pi}} \exp\left(-\left(\frac{\left(A-B\sqrt{\tau_s}\right)^2}{2}\right)\right)$$

If $\dot{P}_d(\tau_s)$ is the first order derivative of $P_d(\tau_s)$ w.r.t. τ_s than

$\dot{P}_d(\tau_s) = \frac{B}{2\sqrt{2\pi\tau_s}} \exp\left(-\left(\frac{\left(A-B\sqrt{\tau_s}\right)^2}{2}\right)\right)$ It is clear that $\dot{P}_d(\tau_s) > 0,\ \forall\, \tau_s$

Similarly if $\ddot{P}_d(\tau_s)$ is the second order derivative of $P_d(\tau_s)$ w.r.t. τ_s than

$\ddot{P}_d(\tau_s) = \frac{-B}{4\tau_s\sqrt{2\pi}} \exp\left(-\left(\frac{\left(A-B\sqrt{\tau_s}\right)^2}{2}\right)\right)\left(\frac{1}{\left(\sqrt{\tau_s}\right)} + B\left(A - B\sqrt{\tau_s}\right)\right)$ It is clear that $\ddot{P}_d(\tau_s) < 0$

$\forall\ \left(A > B\sqrt{\tau_s}\right) \equiv \tau_s < \left(\frac{Q^{-1}(\bar{P}_f)}{\gamma\sqrt{f_s}}\right)^2$ hence $P_d(\tau_s)$ is a concave function of τ_s

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