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Design and development of optimal system architecture of cognitive radio for mobile adhoc network overlaid on hetereogenous network (4G)

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Design and Development of Optimal System Architecture of Cognitive Radio for Mobile Adhoc Network Overlaid on Heterogeneous Network (4G)

By

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A thesis submitted in partial fulfilment of the University's requirements for the Degree of Doctor of Philosophy

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Research carried out at

M.S Ramaiah School of Advanced studies

CERTIFICATE

*This is to certify that the Doctoral Dissertation titled "**Design and Development of Optimal System Architecture of Cognitive Radio for Mobile Adhoc Network Overlaid on Heterogeneous Network (4G)**" is a bonafide record of the work carried out by Mr. Nagendra Nagaraja in partial fulfilment of requirements for the award of Doctor of Philosophy Degree of Coventry University*

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NOMENCLATURE

Abbreviations

2G	**2^{nd} Generation cellular communication**
3G	**3^{rd} Generation cellular communication**
4G	**4^{th} Generation cellular communication**
5G	**5^{th} Generation cellular communication**
3GPP	**3^{rd} Generation Partnership project**
AWGN	**Additive White Gaussian Noise**
BPSK	**Binary Phase Shift Keying**
CDMA	**Code Division Multiple Access**
CR	**Cognitive Radio**
CSI	**Channel Sate Indicator**
D2D	**Device to Device communication**
dBm	**decibel-milliwatts**
FPGA	**Field Programmable Gate Array**
GPU	**Graphics Processing Unit**
IoT	**Internet of Things**
LDPC	**Low Density Parity Check Codes**
LTE	**Long Term Evolution**
LTE-A	**Long Term Evolution-Advanced**
MANET	**Mobile Adhoc Network**
MIMO	**Multiple Input Multiple Output**
OFDMA	**Orthogonal Frequency Division Multiple Access**
PU	**Primary User**
Qspec	**Quality of Service specification for Primary User**
QPSK	**Quadrature Phase Shift Keying**
SISO	**Single Input Single Output**
SINR	**Signal to Interference Noise Ratio**
SNR	**Signal to Noise Ratio**
SVM	**Support Vector Machine**
OFDM	**Orthogonal Frequency Division Multiplexing**

ABSTRACT

This thesis presents novel architectures and algorithms to improve the spectral efficiency of Cognitive Radio (CR) systems using 3-Dimensional Spectrum Sensing (3DSS) and Support Vector Machines (SVMs). Spectrum sensing requires CR nodes to co-operate with each other to sense the presence of a Primary User (PU) to avoid the hidden node problem (Ian F. Akyildiz, 2009). This thesis presents a novel scheme for assigning the resources for sensing and communication based on the distance estimated using path loss curve. The thesis proposes controlled co-operative spectrum sensing to enhance the spectral efficiency and throughput of the CR network. In the proposed controlled co-operative spectrum sensing, time, frequency and distance of CR nodes to fusion centre are assigned through a fusion centre to enhance the effective spectrum sensing of the CR system. Unlike the conventional CR systems where the spectrum sensing is in frequency domain only, this thesis proposes 3DSS in space, time and frequency domains to reduce the overall probabilities of false alarm and missed detection. Further, MANET is overlaid on a heterogeneous network to offload signalling and functions of the fusion centre. Overlaying MANET on the infrastructure based heterogeneous network makes link establishment and maintenance more robust and hence improves the success of CR deployment on the MANET. This thesis proposes 3DSS routing algorithm in CR enabled MANET (CRMANET) to improve the throughput of CRMANET network. The 3DSS and the 3DSS routing algorithm are used to update route tables used for link routing in CRMANET. Stochastic Gradient Descent (SGD) is used to perform error correction to the route table of CRMANET. This thesis provides a framework for the adaptive update of the route table using SGD. SGD provides error correction through error backpropagation mechanism over route table of MANET and hence it is far more efficient than static updates based on the long-term feedback of the network. Since characteristics of wireless channel change rapidly according to location, time and frequency usage, a 3-dimensional SGD implemented in time, frequency and space domains provides better routing error correction. Simulation results reveal 200% increase in spectral efficiency over the existing methods of spectrum sensing deployed in CRMANET.

Chapter 1 - Introduction

Wireless communication technology continues to experience the spurt of technological advancements on its quest of impacting positively on the quality of day to day activities of the mankind. During the decades of recent past, wireless communication engineering is probably the only field of technology to compete with the ever-evolving computer technology when viewed with the perspective of their assertion on growing relevance and contemporary technological advancements in meeting the ever-growing demands of the stake holders. Despite the multifaceted tremendous advancements of wireless technology, growing demand for increased spectrum bandwidth and the prevalent severe shortage of bandwidth available in licensed frequency bands allocated to wireless communication devices , continue to be a daunting challenge to meet the demands of the users of wireless technology. The advent of the Internet of Things (IoT) is contributing to the already severe challenge of scarcity of spectrum in meeting the ever-compounding demands of the users. There are about 5 billion connected devices across the world and this count is increasing every minute. To address the need for increased usage of wireless communication with limited wireless spectrum, there is a need for developing effective methods to increase an efficient use of the spectrum. Spectrum efficiency can be increased either through better modulation, signal processing or through efficient allocation and usage of spectrum. Techniques used for improving spectral efficiency using better modulation scheme and signal processing have reached near information theoretical limit. Hence there is a requirement to explore improving the spectral efficiency through spectrum agility. Traditionally, wireless resource allocation is more of a static nature and allocation of spectrum to device is usually for a single purpose application of cellular communication. This model has resulted in 80% of the spectrum being underutilized (FCC Report ET Docket No. 02,135, Nov. 2002). Spectrum agility and Cognitive Radio (CR) are needed to ensure that spectrum utilization is efficient enough to address the scarcity of wireless spectrum.

Spectrum agility implies shift of using wireless resources time, frequency and space (t,f,d) from a noisy wireless spectrum to a spectrum which has lower interference temperature (FCC Report ET Docket No. 02,135, Nov. 2002). This eventually facilitates better quality of wireless spectrum, reduced interference and enhanced wireless spectrum efficiency. The resulting challenges from spectrum agility to be addressed are detection of wireless spectrum holes (unused spectrum) and reducing interference to licensed user or Primary User (PU).

Digital Signal Processing (DSP) has enabled a substantial number of innovations in wireless communication. Comprehensive DSP techniques used in CR are addressed in [(Salma Bourbia, 2012), (Xu Dong, 2010), (Abhinaba Banerjee, 2014), (Jun Ma, 2009), (Ying-chang Liang,2009), (Ghurumuruhan Ganesan, 2008), (Lan Zhang,2008), (Qi Qu, 2008), (B. Pursley,2008), (Stefan Geirhofer, 2008), (Carla-Fabiana Chiasserini, 2012), (Jacques Palicot, 2012), (R. Chandramouli, 2010)]. For the classification and object detection, machine learning and statistical learning are extensively used due to their ability to approximate utility functions. In the detection of PU, signal is still processed using DSP techniques of energy detection and cyclo-stationary detection of signals. But to avoid interference to PU, machine learning techniques, like Support Vector Machines (SVM) are more effective. Detection in all 3 dimensions namely: space, time and frequency with SVMs provides better detection probabilities and hence better throughput of the CR network and lesser interference to PU.

Heterogeneous network architecture enables use of different air interfaces. It can accommodate both long range and short-range communication. Overlaying shorter range Mobile Adhoc Network (MANET) onto the Long-Term Evolution (LTE) enabled 4G/5G networks leads to CR enabled Mobile Adhoc Network (CRMANET). MANETs are used for shorter range and shorter duration networking. To manage mobility and to maintain the link efficiency of MANET, CR deployment on it is necessary. CR provides optimal spectrum and hence facilitates improvement in link efficiency of MANET. CRMANET has to overcome issues of link reliability and hidden nodes to enhance the link efficiency in MANETs. Wireless networks without infrastructure are inherently susceptible to the hidden node problem. Hidden node has been a research topic of considerable importance in MANET and many techniques are in vogue to mitigate the problem of hidden node. This thesis proposes a co-operative sensing technique as yet another scheme to overcome the problem of hidden node in MANET.

1.1 Cognitive Radio and Spectrum Agility

CR is defined as ways to build intelligence into radio communication. Radio can be intelligent in many ways as defined in (Joseph Mitola, 2000). In the proposed thesis, the spectrum agility part of CR is considered. Spectrum agility is defined as a process of occupying an optimal spectrum band for wireless communication from currently used spectrum band by a CR node to maximize the throughput and spectral efficiency of the wireless network. PU of the spectrum is defined as the licensed spectrum user of the licensed spectrum band. CR is defined as the user of unlicensed spectrum bands including 2.5 GHz and 5 GHz frequency bands, which are used for Wi-Fi and microwave communication. Spectrum agility is enabled by detecting the spectrum hole by a CR node and shifting the frequency of wireless operation to a spectrum band that is not currently occupied by PU.

1.2 Spectrum Sensing Techniques

Types of spectrum sensing techniques includes energy based, waveform based and cyclostationary based. (Yucek T., 2009) provides a survey of spectrum sensing techniques. Spectrum sensing is mainly divided into two broad classes namely co-operative spectrum sensing and standalone spectrum sensing. In co-operative spectrum sensing technique, various CR nodes co-operate with each other to sense the PU. In standalone spectrum sensing, each CR node detects PU by listening to the allocated frequency band. Standalone spectrum sensing suffers from issues related to hidden node problem. Hidden node problem or a hidden node is a situation when a transmitter in each frequency band cannot detect if the destination receiver is receiving the information at the same frequency band from another transmitter, which is hidden from the transmitter in the context. This leads to packet collision and hence loss of information at the receiver. This can be avoided using co-operative spectrum sensing. In co-operative spectrum sensing, CR nodes co-operate with each other by exchanging information about the detection of PU. This effectively exposes any hidden PU from CR transmit node.

1.3 Heterogeneous Network and Application on MANET for Spectrum Agility and Cognitive Radio

Heterogeneous network provides application opportunity for spectrum agility and CR. Heterogeneous networks contain many types of air interfaces and hence can work on different frequency bands at the same time. This provides an opportunity for spectrum agility, where a given interface can use best available spectrum through CR or spectrum agility. This increases the spectral efficiency expressed with the unit of bits/sec/Hz and hence more data can be transmitted in each frequency band. MANET is one of the possible air interfaces in heterogeneous network. MANET is deployed on the unlicensed spectrum of 2.5 GHz and 5 GHz bands. Due to lack of infrastructure of the network, the transmission on the MANET is very unreliable. In addition to lack of infrastructure, usage of unlicensed band causes lower Signal to Interference Noise Ratio (SINR) of the communication channel. Unlicensed spectrum in the frequency bands of 2.5 GHz and 5 GHz has range limitation of 100 meters and is subject to interference from microwave transmission. To harness the full potential of MANET, it is necessary to deploy CR on it, which enhances SINR by providing spectrum agility.

1.4 Motivation of Research and Research Questions

Internet of things (IoT) devices are everyday objects that is connected to internet. Examples of such objects are energy meter, Television, Refrigerator, Automotive and furniture. Based on the recent deployment of IoT devices explained in (Tianlong Yu, 2015) and the review of relevant literature on upcoming 5G standards (5G mobile standards, 2011), it is apparent that DSP techniques may not be adequate to increase spectral efficiency. Standalone DSP techniques like energy detectors and cyclo-stationary detectors are not network aware and therefore provides the standalone spectrum sensing efficiency (Yucek T., 2009). The standalone DSP techniques cannot be deployed in commercial applications because of lack of network awareness and hence they fail to provide required improvements in spectral efficiency. To meet the demands of forecasted spectrum usage by wireless devices as suggested in (Tianlong Yu, 2015), spectral efficiency must be increased from existing 16.32 bits/sec/Hz in LTE to 60 bits/sec/Hz. Further, the prevalent spectral efficiency of 30 bits/sec/Hz in LTE-A has to be increased to 60 bits/sec/Hz with LTE-A plus D2D CRMANET on the same network.

Based on the discussions presented in the earlier sections, following observations are evident:

- The massive addition of wireless devices on a continual basis, increases the usage of wireless spectrum
- Many algorithms/schemes of conventional DSP as well as communication engineering are of significant importance for the improvement of spectral efficiency of a communication system
- For example, waveform modulation schemes like Orthogonal Frequency Division Multiple Access (OFDMA) in combination with Multiple Input Multiple Output (MIMO) and error correction codes such as Low-Density Parity check (LDPC) and

Turbo code have significantly improved spectral efficiency; but they are reaching theoretical limits

- It is difficult to avoid hidden node problem in the standalone spectrum sensing
- Co-operative spectrum sensing can provide solution to hidden node problem
- Co-operative spectrum sensing suffers from resource allocation issues, as too many CR nodes which sense the presence of PU increase the sensing time and consume more bandwidth
- Heterogeneous networks offer opportunity to enhance spectral efficiency by using CR
- MANET on a standalone basis cannot support CR and therefore cannot improve the spectral efficiency
- MANET overlaid on the heterogeneous network can support CR and hence can enhance the spectral efficiency of the wireless systems

Some of the significant research issues which appear to have not been addressed in literature include:

- Methods of spectrum sensing for heterogeneous networks
- Controlled Co-operative spectrum sensing
- Establishment of a framework for 3-dimensional spectrum sensing with the 3 dimensions comprising space, time and frequency
- Routing protocol in MANET which considers the spectral agility
- Methods to allocate resources for sensing and communication when overlaying MANET onto heterogeneous networks
- Role of machine learning in spectrum sensing, since various spectrum usage cannot be modelled by a predetermined function or through the empirical models
- Deployment of machine learning in both spectrum sensing and MANET routing protocol needed to enable CR in MANET and heterogeneous networks

- Improvement in spectral efficiency either through increasing link spectral efficiency or through increase of usable bandwidth for communication
- Spectral efficiency solution centred around the increase in availability of usable bandwidth available for CR communication

1.4.1 Research Questions

There is tremendous interest in CR application to improve spectral efficiency within scientific community of both industry and academia. However, improvement in spectral efficiency is a function of underlying spectrum sensing techniques and its integration into larger application space. The application range of CR includes shorter range applications like Device to Device (D2D) communication and MANET. Also, the literature review reflects that spectrum sensing is carried out only in frequency domain. Dimensions of both time and space are not considered in the prior research efforts on CR.

The above discussions give raise to many gaps in the current research efforts in the CR. A summary of the research gaps which warrant further investigations and explorations is as follows:

1. Does controlled co-operative spectrum sensing performs better than the co-operative spectrum without a way to allocate resources?
2. Is it possible to increase available bandwidth and usable bandwidth in a wireless network by using CR techniques?
3. What are the effects of estimation of distance of PU from the fusion centre on the resource allocation and spectrum efficiency improvements?
4. Can CR exploit heterogeneity in network interfaces to increase spectral efficiency?
5. What is the effect of using machine learning on the spectrum sensing techniques?
6. What is the effect of the overlay of MANET on heterogeneous networks to enable the CR applications of MANET?

7. Can the dimensions of space and time be used in spectrum sensing, although some research studies define spectrum hole across space and frequency?
8. How does routing algorithms get modified in MANET, when enabled for CR?
9. What kind of resource structure is required for overlaying CR enabled MANET on heterogeneous networks?
10. Can simple machine learning techniques be applied to improve spectrum efficiency in CR MANET systems overlaid on heterogeneous networks?

1.5 Objectives of Thesis and their Significance

This research is aimed to answer the questions formulated in the previous section. This thesis answers these questions by fulfilling the following objectives:

1. To model the CR system model with system parameters like: Outage probability, Bit Error Rate (BER), Signal to Interference Noise Ratio (SINR), Sensing time, switching time, Number of nodes required to sense PU reliably in co-operative spectral sensing
2. To analyse the feasibility and implementation of CR to enable Mobile Ad-hoc Networks and heterogeneous networks
3. To develop system models for the controlled co-operative spectrum sensing in order to improve the efficiency of CR in Mobile Ad-hoc and heterogeneous networks
4. To implement the controlled co-operative spectrum sensing system model in the Mobile Ad-hoc and heterogeneous networks
5. To implement the controlled co-operative spectrum sensing system model of CR enabled Mobile Ad-hoc network overlaid on 4G network for enhanced efficiency of Mobile Ad-hoc Networks

1.6 Original Contributions of the Thesis

Following are original contributions of this thesis; whose focus is on the system architecture of CR for MANET overlaid on heterogeneous network (4G):

- A controlled co-operative sensing using path loss model of the wireless channel
- A more effective resource allocation strategy for sensing and communication through controlled co-operative spectrum sensing to increase usable bandwidth of wireless channel by CR systems
- Providing a tradeoff between higher and lower frequency allocation to increase the available bandwidth for CR communication
- Providing a network architecture to overlay MANET over heterogeneous networks to enable CR
- Formulating a 3D Spectrum Sensing (3DSS) to reduce the error probabilities and increase the throughput of MANET overlaid on heterogeneous networks
- Proposing a 3DSS routing algorithm for MANET, which doubles the MANET reliability by decreasing detection error probabilities and hence increasing the throughput of MANET

1.7 Organization of the Thesis

This thesis is organized into 8 chapters. This section briefly describes the contents of each chapter of the thesis.

Chapter 2: This chapter provides the necessary background theory and review of literature on various theoretical concepts to facilitate better appreciation of the research proposed in the thesis. It introduces basic concepts of CR and spectrum sensing. It also dwells the mathematical analysis behind the spectrum agility. It introduces detection theory which is the basis for detecting PU in CR system. This chapter also presents a brief conceptual introduction to various mathematical theories and techniques like Neyman-Pearson criteria, Stochastic Gradient Descent (SGD), Support Vector Machines (SVM), heterogeneous network and MANET. It also discusses the problem with hidden node in MANET as well as the OFDM which is the modulation used in heterogeneous networks.

Chapter 3: This chapter addresses the issue of shortage of spectrum and the need for higher spectrum efficiency. As opposed to traditional way of solving the spectrum efficiency through better modulation schemes and channel error control, this chapter suggests the spectral agility as a means to increase the available bandwidth for wireless communication system. The formula for spectrum efficiency that involves the available bandwidth and usable bandwidth is defined. The same formula is used in the entire thesis to compare the improvement in spectrum efficiency.

Chapter 4: This chapter discusses the implementation of CR in heterogeneous networks and MANET. It brings out the requirements to make CR feasible on the MANET and heterogeneous networks. It analyses various CR parameters to conclude the feasibility of CR on MANET and heterogeneous networks.

Chapter 5: This chapter deals with the original contribution of the thesis pertaining to the controlled co-operative spectrum sensing. In controlled co-operative spectrum sensing, regression is performed on wireless path loss curve to determine the distance of the PU from the fusion centre. The estimated distance vector is used to assign the resources for sensing. This chapter also presents the simulation setup and results obtained for controlled cooperative spectrum sensing.

Chapter 6: This chapter proposes concept of 3DSS. 3DSS is another original contribution of this thesis. This chapter also explains the structure of heterogeneous network considered in this thesis. The machine learning techniques like SVM is used to detect the spectrum holes. Resource blocks needed for either licensed user or CR user are defined in this chapter. Simulation setup of 3DSS and the associated results on 3DSS are also discussed in this chapter of the thesis.

Chapter 7: This chapter introduces the concept of 3DSS routing algorithm for CRMANET overlaid on the heterogeneous network. 3DSS routing algorithm is formulated for its exclusive application to CRMANET. Formulation of 3DSS routing algorithm is yet another original contribution of this thesis

Chapter 8: This chapter presents a summary on the results, conclusions and possible inferences derivable through the various analyses and the results of simulation studies presented in this thesis. A discussion on possible future avenues to explore further research studies on the topics/issues covered in this thesis is also presented in this chapter.

1.8 Publications Associated with this Thesis

Sl. No	Title	Journal / Conference details
1	**Co-operative Spectrum sensing using CR node binary decision regression on estimated wireless path-loss curves**	ICECS-2014, IEEE Conference Paper
2	**3D Spectrum hole detector using Support Vector Machine to enable D2D overlay on the heterogeneous CR network**	ICEDS-2017, IEEE Conference Paper

Chapter 2 - Review of Background Theory

This chapter is aimed to present a succinct review of concepts, techniques and theories essential for comprehensive grasp of scope and the associated novelty of the results of the thesis. The scope, relevance and underlined concepts of CR are explained with requisite details keeping the perspectives of background theory of research. Neyman Pearson Criteria and Theory of Signal Detection which are necessary background are also covered in this chapter. Neyman Pearson Criteria explains the performance optimization of CR systems. Theory of signal detection lays theoretical foundation for CR system models developed in this research. The wireless link for transmission and for spectrum sensing plays a major role in CR system. When network has different types of air interfaces, they are called Heterogenous networks. Heterogeneous networks are part of ongoing evolution in infrastructure-based networks. Long Term Evolution (LTE)-Advanced provides the definition of heterogeneous networks used in 4G standard. The emergence of LTE and the significance of infrastructure based heterogeneous networks are also discussed. There is an emphasis on MANET in this chapter since it is one of the key concepts in the proposed research. Two bigger issue of "Hidden nodes" and link reliability of MANETs are covered. Various routing algorithms used in MANET is introduced. Field of machine learning is also constituting important part of this research. This chapter also covers the conceptual details of SVM which is a basic classifier under the purview of Machine Learning. For MANETs unconstrained optimization of link routing is very important. SGD is known for solving unconstrained optimization problem. SGD is explained in detail with basic mathematics behind its application.

2.1 Cognitive Radio

In the context of this research CR means spectrum agility. The concept of CR first arises from the PhD thesis of Joseph Mitola III given in (Joseph Mitola III, 2000). The basic cognitive cycle is defined as in Figure 2.1.

Cognitive cycle involves interaction with outside world to come up with cognition cycle to provide software control. Computer cognitive cycle involves planning and acting on the RF stimuli received from outside world. By deploying right software and algorithms, the CR is envisioned to take appropriate actions, plan contingency and increase reliability. To complete this theory S. Haykin introduced signal processing perspective of CR in (S. Haykin, 2006) and (S. Haykin, 2005). This involves much more mathematical rigour and lays foundation to current research work in this thesis.

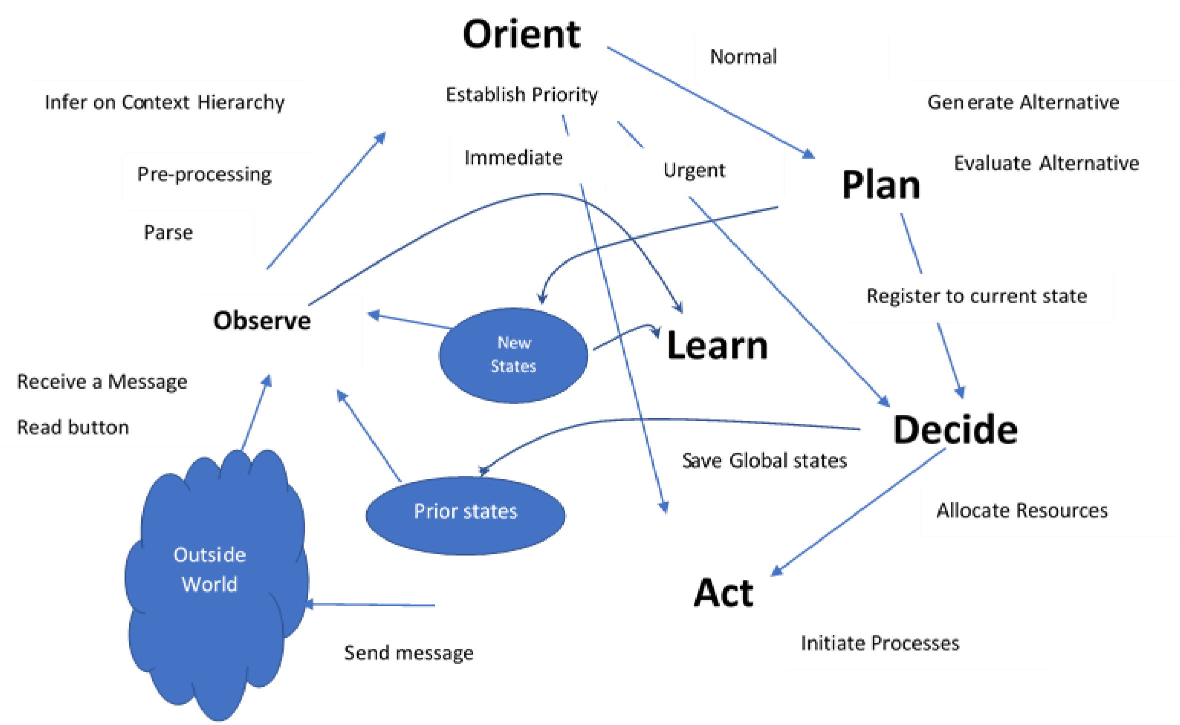


Figure 2-1 Cognitive Cycle

Figure 2.1 explains the cognitive cycle in a radio environment. The cognitive cycle involves interaction with the outside world, which consists of mainly radio environment. Observation from radio environment is obtained and same is processed to obtain actionable information. CR orients itself using actional information, It also establishes priority of next steps. It plans its next action, learns from its action and decides on typical resource allocation. This complete the cognitive cycle in the radio environment. Cognitive cycle follows a state machine transition between prior states and next state.

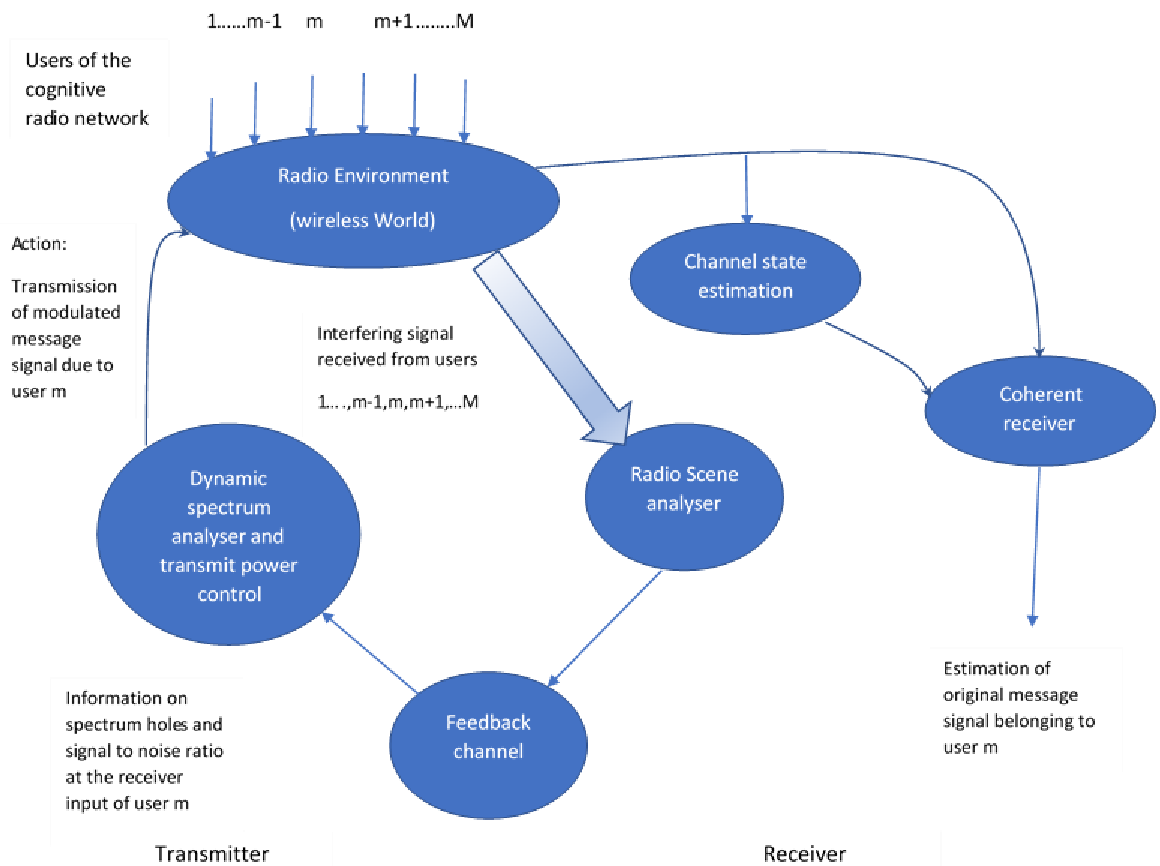


Figure 2-2 Theory of Cognitive Radio Spectrum Agility

According (S. Haykin, 2006), the CR has following operations: Radio-Scene analysis, Channel identification and Dynamic spectrum management. This is shown in Figure 2.2 The first two operations are carried out by receiver of communication system and last task is carried out by the transmitter. Apart from these cognitive tasks, the wireless communication system also needs to perform the channel state estimation through Channel State Identification (CSI), obtain feedback for interference mitigation and spectrum switching. Dynamic spectrum management also involves Transmit Power Control (TPC). Most CR problems can be either solved through the high sensitive receiver or through TPC. Considering the physical limitations of receiver sensitivity and noise floor of current generation of receivers, advanced interference avoidance must be achieved through TPC. Another important measure in CR technologies as well as in wireless communication is *Interference Temperature*. As noted in (Ekram Hossain, *et al.*, 2007**)**, current wireless communication system is transmitter centric. The noise floor of receiver not only depends on distance from the transmitter, but also on the interference from other signal sources. (ET Docket No. 02,135, FCC) is the special task force report from Federal Communication Commission (FCC), which defined interference temperature of the network.

The concept of interference temperature is identical to that of noise temperature. It is a measure of the power and bandwidth occupied by interference. Interference temperature T is specified in Kelvin and is defined as TI(fc, B) = PI(fc, B)/ kB , where PI(fc, B) is the average interference power in Watts cantered at fc, covering bandwidth B is, measured in Hertz. Boltzmann's constant k is Joules per Kelvin degree

Interference temperature is intended to manage total interference in radio environment. This is a dynamic quantity and is required to be managed adaptively. Interference temperature provides the worst-case scenario for the wireless environments. This is the specification limit beyond which the wireless network may not function with average expected performance. As shown in Figure 2.2, the model for spectrum agile network consists of PU, CR and interference management methods to reduce the interference to PU and provide best possible throughput in the CR network. In this setup, interference temperature provides the limit on RF power the CR user can emit in the licensed band which can be tolerated by PU. If the RF power from the CR user raises the noise floor and hence exceeds the interference temperature, it is considered as violation of the interference limit and often even as illegal.

Furthermore, the interference temperature is measured in degrees Kelvin and calculated from Power Spectral Density (PSD) of a given spectrum band. So, it is very important that to calculate or estimate total interference in the frequency band, there is a need to estimate the PSD very accurately. In the current research, the PSD is modelled through probabilities of detection, thus reducing interference to ensure PSD of the spectrum within limits of usability.

2.2 Theory of Signal Detection and Neyman Pearson Criteria

Signal detection theory is required to test weak signals embedded in the noise. An extensive theory on signal detection is provided in (Steven M. Kay, 1993). Detection can be broadly classified into binary hypothesis and multinomial hypothesis. Concept of binary hypothesis testing is most widely used in signal detection. The same concept is used in this thesis to confirm the presence of PU.

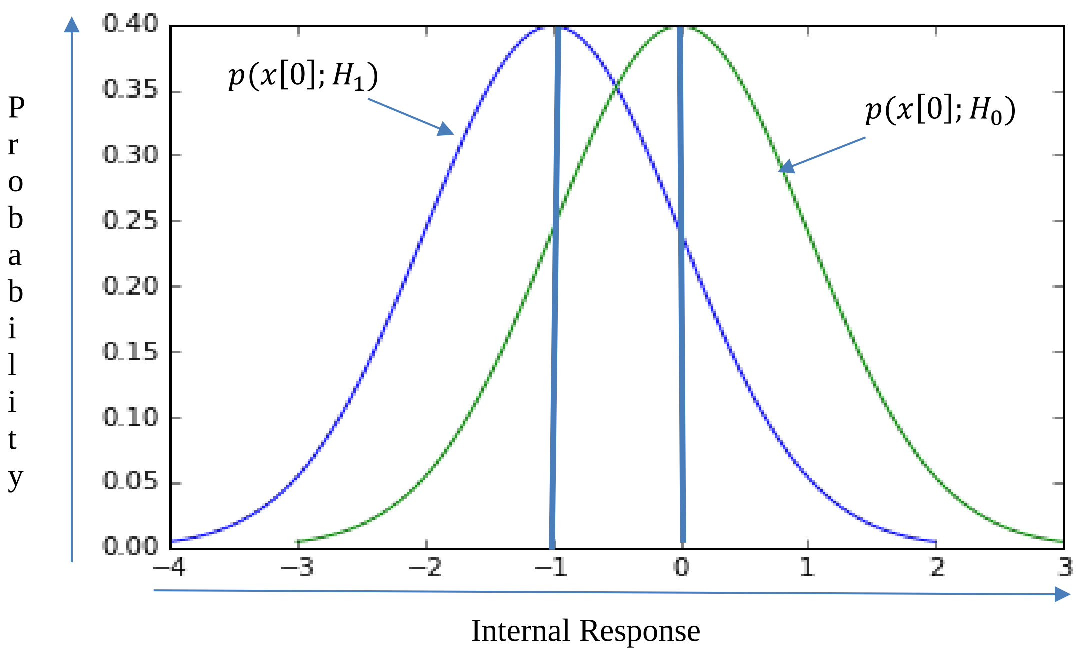


Figure 2-3 PDF for Binary Hypothesis Testing Problem

As shown in Figure 2.3, horizontal axis represents the internal response of the system, which is also system transfer function. Vertical axis represents the probability of the Probability density function. H_0 represents the null hypothesis and H_1 represents the alternate hypothesis. When the signal is embedded in noise, the mean of Probability Distribution function (PDF) will shift randomly, making it difficult to detect. The testing that is performed to detect the signal is called binary hypothesis testing. The two hypotheses can be written as:

$$\mathcal{H}0: \mu = 0$$
$$\mathcal{H}1: \mu = -1$$

Two types of error can be defined in detecting a signal. Type 1 error is when one decides $\mathcal{H}_0$ given $\mathcal{H}_1$ is true. Type 2 error is when one decides $\mathcal{H}_1$ given $\mathcal{H}_0$ is true. It is generally impossible to reduce both the types of error simultaneously. It is a usual practice to hold one of these errors constant and optimize other error. One can define $P(\mathcal{H}_1; \mathcal{H}_0)$ as false alarm, P_{FA} and $P(\mathcal{H}_0; \mathcal{H}_1)$ is missed detection P_M. To design the optimal detector, there is a need to keep P_{FA} constant and minimize the P_M, $(\mathcal{H}_0; \mathcal{H}_1)$. It is equivalent to say to maximize the Probability of detection P_D given by: 1- $P(\mathcal{H}_0; \mathcal{H}_1)$. Probability of detection P_D can be represented as: $P(\mathcal{H}_1; \mathcal{H}_1)$. Given this, Neyman-Pearson theorem suggests maximizing $P_D = P(\mathcal{H}_1; \mathcal{H}_1)$ subject to the constraint $P_{FA} = P(\mathcal{H}_1; \mathcal{H}_0) = \alpha$. Elaborating Neyman-Pearson theorem into Log Ratio Test (LRT), following theorem can be defined. To maximize PD for a given PFA = α, one needs to decide on hypothesis $\mathcal{H}_1$ if

$$L(x) = \frac{p(x;\mathcal{H}_1)}{p(x;\mathcal{H}_0)} > \gamma \qquad (2.1)$$

Where γ is the decision threshold. L(x) is a Likelihood Ratio (LR). Further γ can be solved from

$$P_{FA} = \int_{\{x:L(x)>\gamma\}}^{0} p(x;\mathcal{H}_0)\, dx = \alpha \qquad (2.2)$$

Neyman-Pearson theorem forms the basic analysis tool in spectrum sensing. One has to follow Neyman-Pearson approach to constraint the missed detection from a Quality of Service (QoS) specification, to minimize interference to PU. Further another objective is to maximize the throughput of CR by minimizing the P_{FA}. For a given interference specification to the PU network, throughput of CR network is limited by P_{FA} as defined from the Neyman-Pearson theorem.

2.3 Heterogeneous Network

Heterogeneous networks are networks with many types of RF interfaces for communication. Heterogeneous networks complement the Third generation (3G) wireless network to enable usage of wider and new spectrum, flat IP (Internet Protocol) architecture and increased mobility. These features were not possible in 3G networks. Long Term Evolution –Advanced (LTE-A) incorporates many heterogeneity features in the network architecture. Some of them include, support of repeaters to increase SNR, support for Femto cells to provide better signal strength for indoor access and support for unlicensed band usage for off-loading heavy cellular traffic loads. (Khandekar A., 2010) provides an overview of LTE-A heterogeneous networks. (Mingrui Zou, 2008) suggests use of Amplify and Forward (AF) and Decode and Forward (DF) relays for spectrum sensing functions. Relays are a part of heterogeneous network architecture to help in enhancing the SINR at the edge of the network. (Serrador A., 2008) suggests various performance parameters to evaluate heterogeneous networks. Throughput improvement is most important parameter.

Figure 2.4 shows the heterogeneous network architecture in LTE-A. Compared to 3G networks, where air interfaces are homogeneous, 4G and 5G networks use heterogeneous architecture, with diverse types of air interfaces and network elements. In 3G networks, the air interfaces are used to connect mobile terminal and the base stations. In heterogeneous or 4G/5G networks, there is hierarchy in physical layer. But network lawyer is a flat IP network. Heterogeneous networks are also well structured to deploy spectrum agility with the help of hierarchy of subnets. Each subnet can be individually configured as a CR network or PU network.

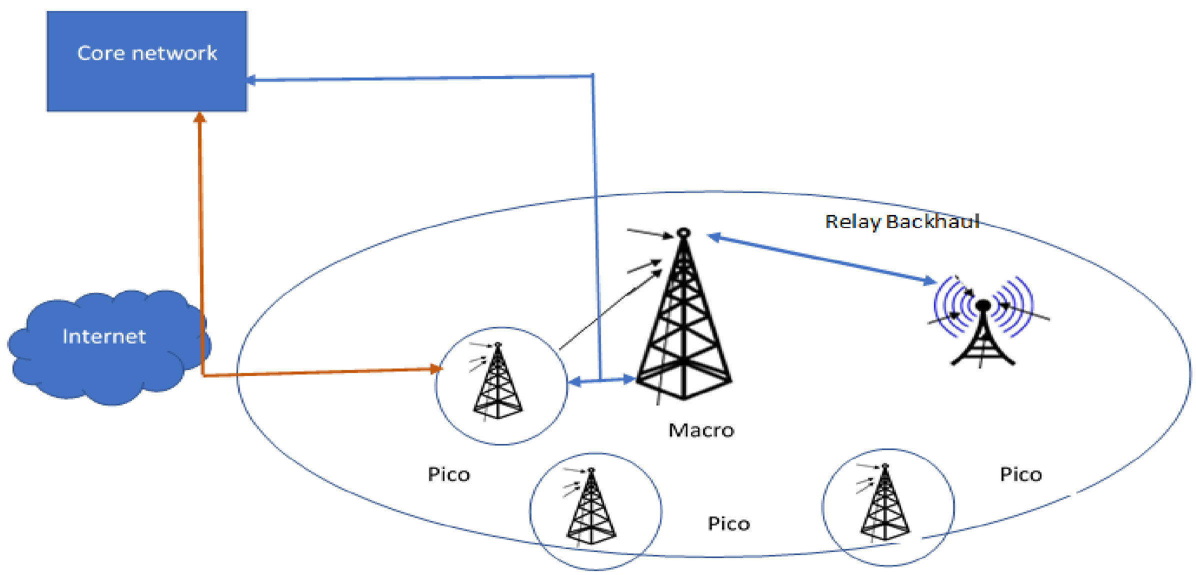


Figure 2-4 Heterogeneous Network Used in LTE-A

As shown in Figure 2.5, each subnet can be configured into CR enabled and secondary user subnet. Further each subnet will have its own base station that connects with macro base station of primary network. CR subnets also co-operate among themselves to provide spectrum agility. Heterogeneous networks can also provide better infrastructure to overlay Device to Device (D2D) communication, by establishing initial signalling and providing CR resource maps. With the advent of 5G, even millimetre wavelength air interface is used for signalling the network and improving SINR of the network.

In addition, channelization of heterogeneous network is flexible with Orthogonal Frequency Division Multiplexing (OFDM) waveform. The resource blocks are assigned in both time and frequency. Each resource blocks allocated to channel is granular enough to enable spectrum agility at both base station level as well as at the shorter distance D2D communication. Orthogonal Frequency Division Multiple Access (OFDMA) channelization also supports wider communication channel, with lower channel spacing. OFDM waveforms can be applied at different frequency bands simultaneously.

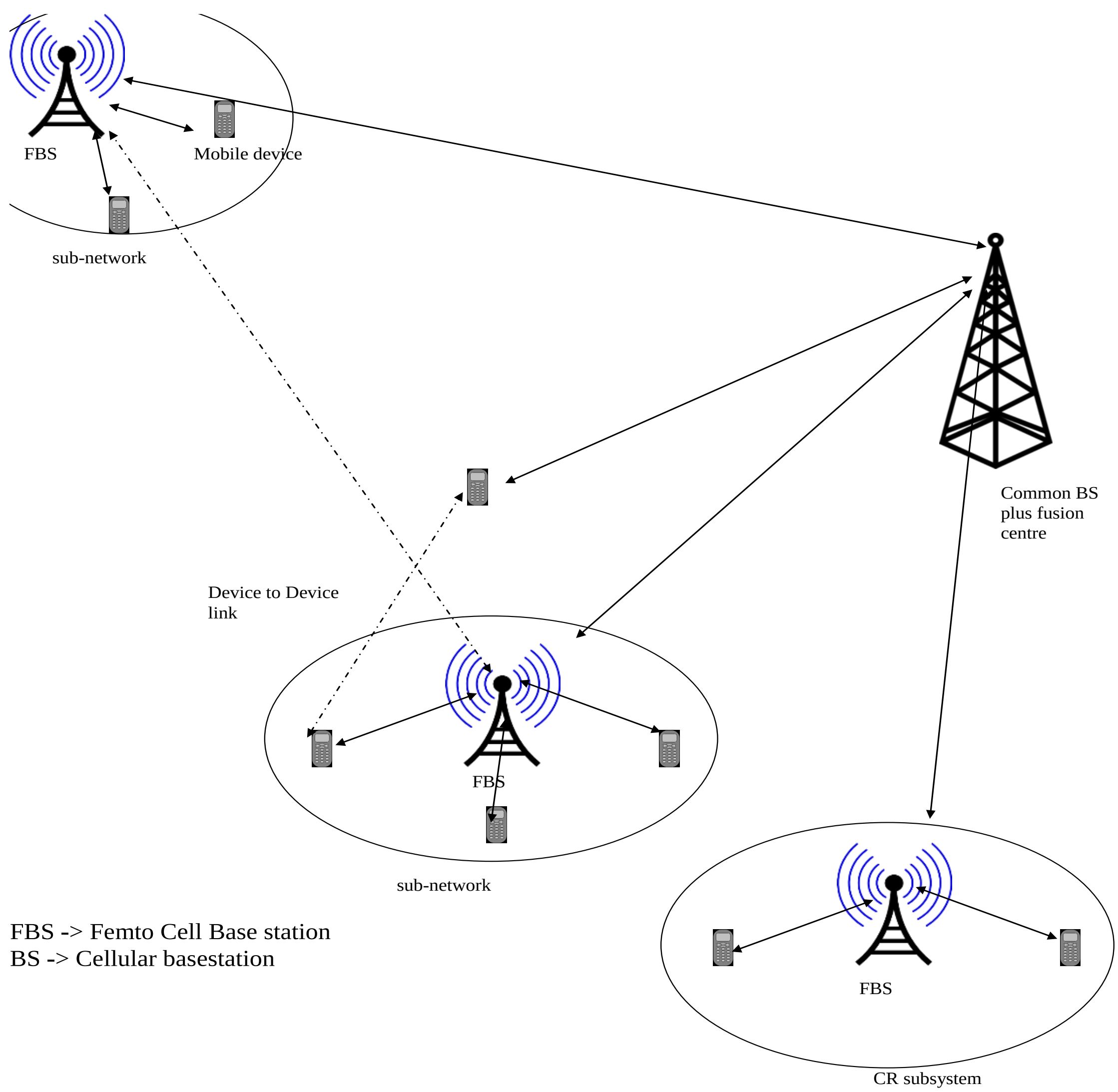


Figure 2-5 Example of CR and PU Subnets in CR Enabled Heterogeneous Network

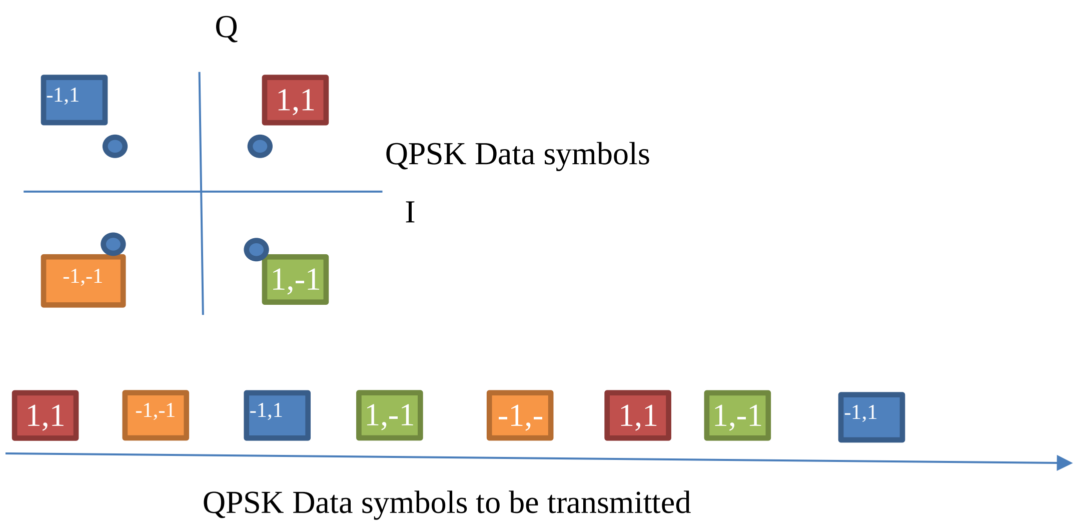


Figure 2-6 QPSK Data Symbol

Since CR and PU use different frequencies at a time, it is possible to have OFDM symbols with both CR and PU communication combined.

Figure 2-6 describes example data symbols transmitted on OFDM. OFDM symbols can be of diverse types. Figure 2.7 shows the OFDMA downlink in LTE.

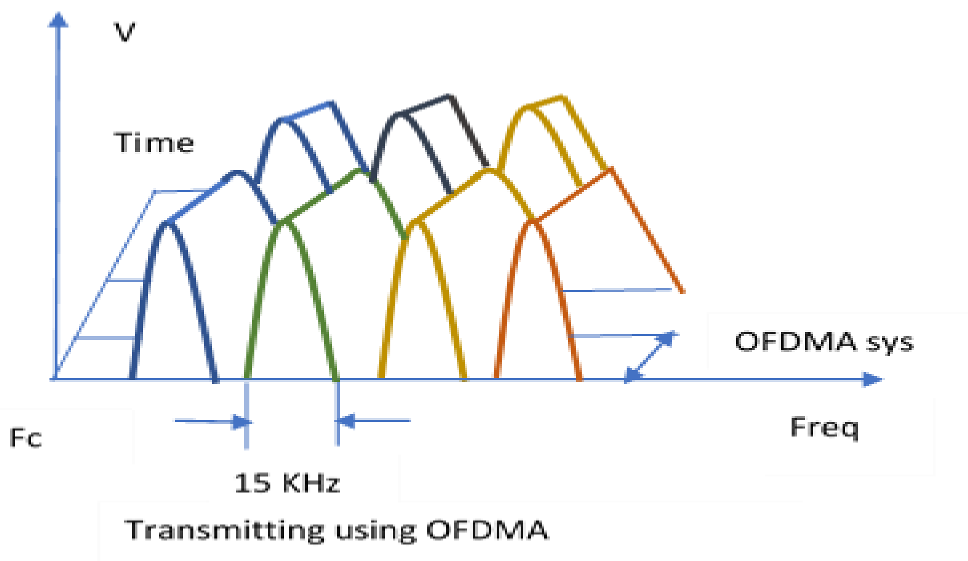
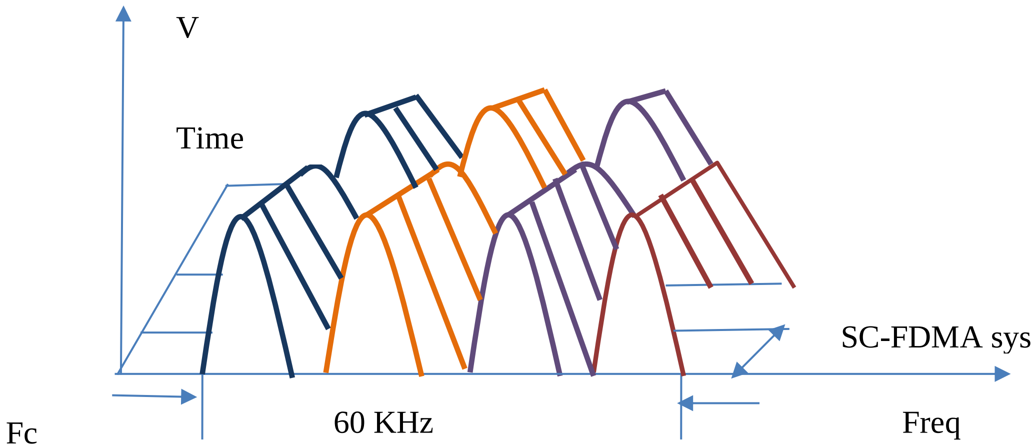


Figure 2-7 OFDMA Symbols for LTE Receiver

Figure 2.8 shows Single Carrier- Frequency Division Multiple Access (SC-FDMA) for uplink. Using OFDMA for downlink and Single Carrier- Frequency Division Multiple Access (SC-FDMA) for uplink. SC-FDMA is used for uplink to avoid the Peak to Average Power Ratio (PAPR) issues, which drive the transmit power amplifier to saturation or results in lower transmit power efficiency. Modulation of these symbols can be through QPSK, QAM-16 and QAM-64. OFDM symbols in either case is can be shared between CR communication and PU with either 15 kHz spacing or with 60 kHz band symbols. The transmit and receive chains of the OFDM transceivers are shown in Figure 2.9.



Transmitting using SC-FDMA

Figure 2-8 Symbols of SC-FDMA

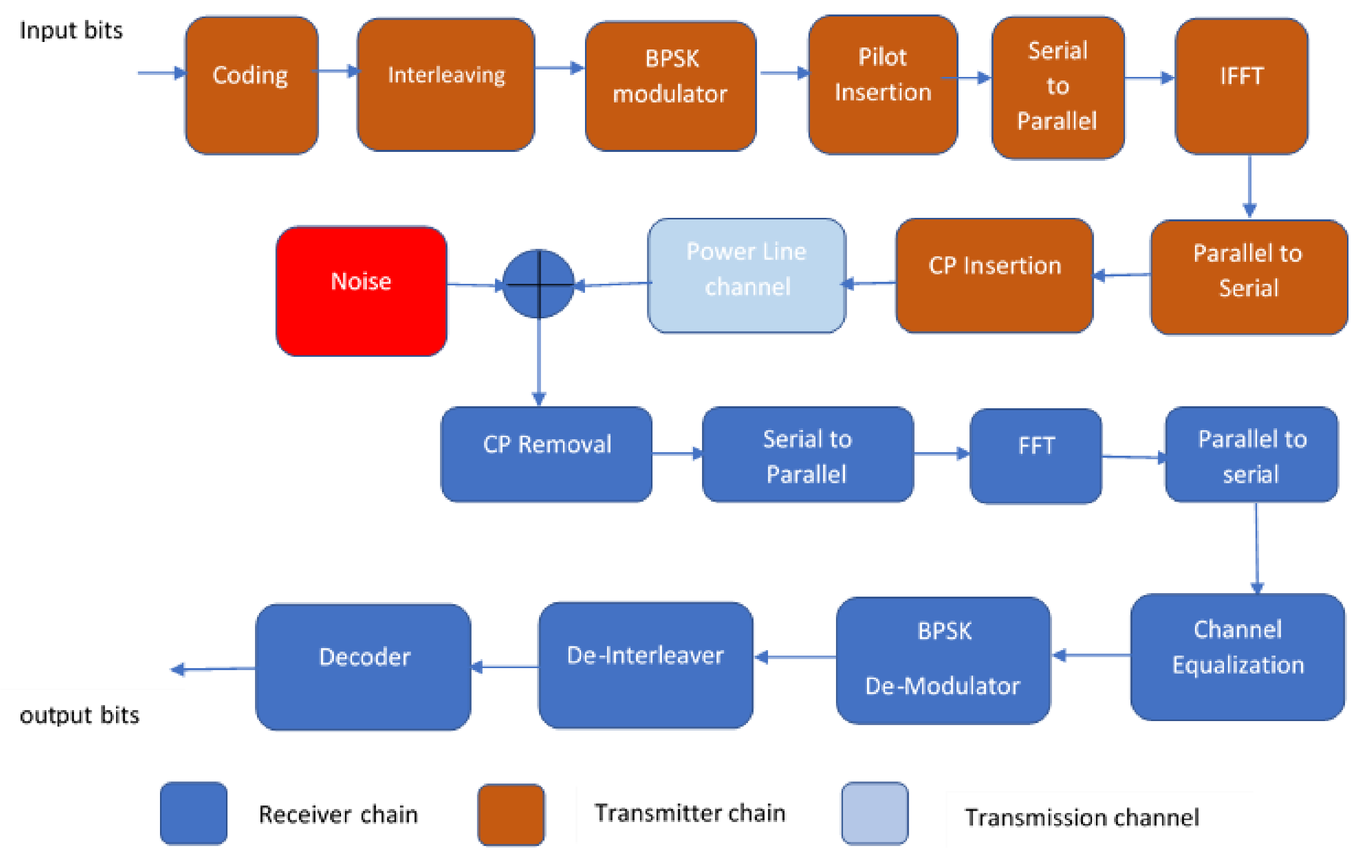


Figure 2-9 An Example of OFDM Modem

Typical OFDM modem contains different blocks shown in the Figure 2.9. It consists of both transmitter and receiver blocks. Each block represents different function performed by the OFDM modem. Coding block performs channel coding. Channel coding is a form of block codes or convolutional code. Typically, turbo codes or Low-Density Parity Check (LDPC) codes are used in OFDM. BPSK (Binary Phase Shift Keying) modulation is used to modulate the carriers. Interleaving is done obtain the protection against deep fades. Interleaving can be time interleaving or frequency interleaving. OFDM modem uses both time and frequency interleaving. Pilot insertion is used for channel estimation and acts as reference in OFDM. Serial to parallel converter is used to parallelize the transmission of carrier. CP (Cyclic Prefix) insertion is done to recover from ISI (Inter Symbol Interference). Fast Fourier Transform (FFT) is used for demodulation and Inverse Fast

Fourier Transform (IFFT) for modulation. After CP prefix insertion the OFDM modulated signal is transmitted over the channel. OFDM transmission is carried through multiple carriers with orthogonality. Most modern communication systems use OFDM. Examples are Wi-Fi 802.11a/n/ac, LTE and LTE-A. CR communication potentially can be enabled by use of OFDM physical layer. Both modulation schemes and the symbol construction enable CR deployment and spectrum agility by combining CR and PU transmission on single OFDM symbol.

(Ghosh R., 2009) suggests the structure of heterogeneous networks based on graphs. Graph theory plays a key role in optimization of heterogeneous networks. (Tang Long Chi, 2010) suggests CR enabled heterogeneous networks. (Tang Long Chi, 2010) also suggests the reconfigurable CR heterogeneous network, which are based on open architecture and support multimode devices.

2.4 MANET

Mobile Adhoc Networks (MANETs) are mainly used for D2D communication, without an intermediate infrastructure to relay the data. MANET based devices are assumed to be mobile and support different protocols to carry data across networks. MANET is best placed to be the most important beneficiary of technologies of spectrum agility.

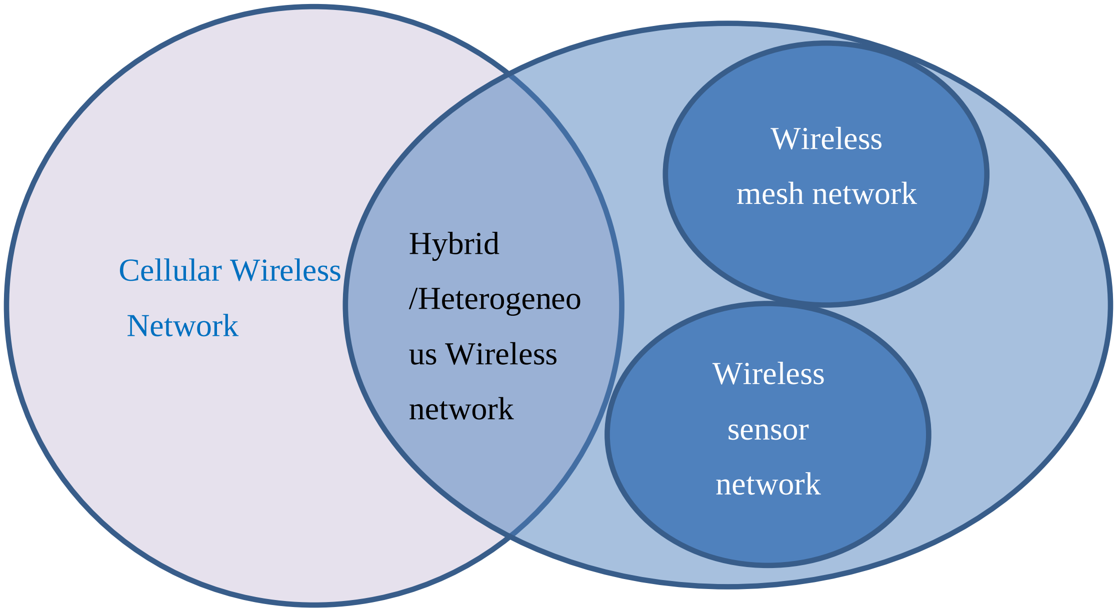


Figure 2-10 Cellular Network and Ad Hoc Networks

Wireless networks can be broadly subdivided as shown in Figure 2.10. Cellular networks rely on the infrastructure to support their communication. Wireless ad hoc networks are self-organizing. Examples of ad hoc networks are Wireless mesh networks and sensor networks. Sensor networks are used in the case of wireless sensors deployed in the special applications, which require low power consumption and longer battery life. Sensor networks usually do not have mobility requirements. Sensor networks also have substantial number of nodes. Some of the applications of sensor network includes military, security and oil and gas exploration. Various sources of the energy in sensor networks are replenishable energy source and non-replenishable energy sources. Bandwidth and traffic characteristics of the sensor network make it a requirement to have very high reliable links and lower bit rates.

Wireless mesh networks are ad hoc networks that are used as alternate to cellular networks to provide infrastructure which does not require extensive network planning. Apart from planning, mesh network does not incur any spectrum reuse constraints that are present in cellular networks. As explained in (H. Wu, 2001), the integrated Cellular Ad hoc Relay (iCAR) networks were one of the applications of hybrid network. Overlay of ad hoc relaying has been explored in wireless communication industry over a considerable period of time. However, ad hoc networks suffer from issues which should be solved with elegant engineering solutions. Some of the issues that MANET suffers from are:

1. Medium Access Control (MAC) design, which will be relatively very complex due to the absence of infrastructure
2. Routing protocols suitable to MANET
3. Multicasting, to provide control signals to neighbouring nodes without increasing overhead of protocol
4. New Transport Layer protocol, since current TCP protocol cannot be used as it is defined by Internet Engineering Task Force (IETF)
5. Link reliability: Although part of MAC layer, this is very important issue to be solved
6. Scalability: Since the network control is a cross-layer design, scalability is a serious issue in MANET
7. Security: Securing MANET requires co-operation between nodes and to eliminate rogue nodes. This incurs additional overhead of the protocol

Apart from these key issues discussed above, hidden nodes are major problem in CR enabled MANET.

2.4.1 Hidden Node in MANET

Hidden nodes problem are the issues unique to the wireless networks. This is a serious problem in MANET because of absence of infrastructure to alleviate the issue. The MAC protocol setup by short range protocols like WLAN, Bluetooth and sensor networks, requires negotiating transmitter and receivers to use a wireless communication channel. In hidden node issue, the transmitter fails to recognize the packet sent by one of the terminal nodes, which is in proximity of receiver but far from transmitter. Following this, transmitter node sends the packet to receiver, which will collide with the packet that is sent out by one or more terminal nodes which are hidden from the transmitter but are closer to receiver.

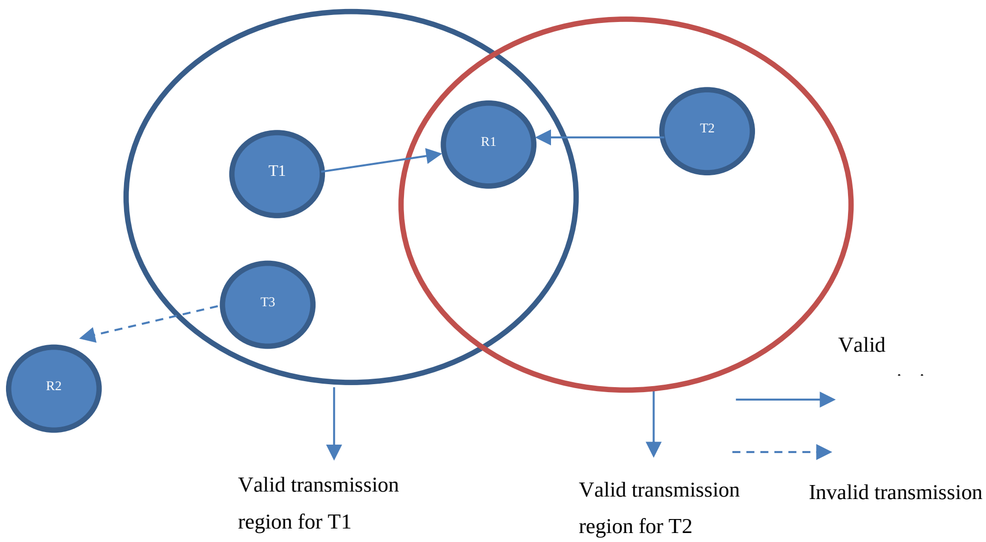


Figure 2-11 Hidden node issue in MANET

As shown in Figure 2.11, hidden node problem is when transmitters T1 and T2 transmit to Receiver R1 simultaneously, because T1 and T2 are hidden from each other. This leads to collision in packet transmission and hence reduction in throughput of the network. In CR, this also becomes an interference issue with PU from a CR user. The derivative problem of the hidden nodes is exposed terminal problem. This is where a transmitter node will be unable to transmit because it will be blocked by nearby transmitter node.

2.4.2 Routing Protocols in MANET

There are many types of routing protocols in MANET. Two important considerations while designing the routing protocols are battery life and processing power. Most MANET nodes will have lower processing power as well as less battery power. Apart from these, most MANET nodes require to be semi mobile or portable. This imposes another constraint of weight and form factor of the node to be less. With these constraints, as suggested in (C. Siva Ram Murthy et al., 2001) ideal routing protocol should exhibit the following features:

1. Must be fully distributed
2. Should adapt to change in topology
3. Route computation and maintenance should involve minimum number of nodes
4. Routing should be localized as global state maintenance involves huge overhead
5. Should have no loops and stale routes
6. Minimize packet collision if MAC is based on Carrier Sense Multiple Access/collision detection (CSMA/CD) or Carrier Sense Multiple Access /Collision Avoidance (CSMA/CA)
7. Convergence to optimal routing should be quicker. Long convergence time will result in performance degradation of MANET
8. Efficient use of resources like battery, processing power and communication bandwidth
9. Nodes should store only states of stable network topology
10. Support for certain level of Quality of Services (QoS) and time sensitive traffic

There are wide range of routing protocols as defined in (C. Siva Ram Murthy *et al.*, 2009). Main classification is based on the following considerations.

1. Routing information update mechanism
2. Use of Temporal information for routing
3. Topology information organization
4. Miscellaneous classifications based on utilization of specific resources

The routing protocol used in this research is based on Sl. No. 4, where spectrum-based routing protocol is designed. Some of the widely used routing protocols in MANET are:

1. Destination Sequenced Distance-Driven (DSDV) Routing protocol
2. Wireless Routing Protocol (WRP)
3. Cluster-Head Gateway Switch Routing Protocol (CGSR)
4. Optimized Link State Routing (OLSR)
5. Fisheye State Routing (FSR)
6. Hierarchical State Routing (HSR)
7. Gateway Switch Routing(GSR)
8. Ad Hoc On-Demand Distance Vector(AODV)
9. Signal Stability based Adaptive (SSA) Routing
10. Flow-Oriented Routing Protocol (FORP)
11. Preferred Link Based Routing(PLBR)
12. Power Aware Routing(PAR)
13. Location Aided Routing(LAR)

Among these routing protocols, one can apply most of them to CR, with the inclusion of the spectrum agility requirements. In this thesis, DSDV or WRP are chosen to simplify the protocol and enhance the focus on actual benefits of the spectrum agility in the MANET. Both DSDV and WRP protocols are table driven routing protocols. Although, table driven protocols may have limitations in quick adaptability to changing network topology and scalability, one can still demonstrate the benefits of spectrum sensing using these protocols to start with.

2.5 Machine Learning and SVM

Machine learning is emerging as de-facto standard for classification. Spectrum sensing is a way to classify that spectrum which is occupied by the PU from that, which is vacant and ready to be used by CR user. Machine learning can play a key role in spectrum management. Considering existing classifications techniques, like neural networks, SVM, Naïve Baysean and K-means clustering, SVM provides very attractive property for classification with high degree of accuracy. SVM was developed by Vladimir Vapnik in 1990s. SVM is not only good at classification, but it also optimizes decision boundary, by adding margin to decision boundary. SVM is a supervised learning classifier which is used for classification, regression and outlier detection. The theory of SVM is based on the mechanism in which SVM outputs the classification hyper planes given the input labelled training data. In addition to performing linear classification with high degree of accuracy, SVM is also good at performing non-linear classification, by mapping inputs to high dimensional feature space. This process is referred to as Kernel trick. Kernel trick is converting low dimension non-separable classes into high dimension separable classes through a kernel transformation.

A hyperplane is defined as flat sub space having N-1 dimensions in an N dimensional space. Classes of data scattered in a plane, can have many hyperplanes dividing them as given in Figure 2.13. Figure 2.13 shows two classes of data and many possible hyperplanes. red coloured circles is class 1 and blue coloured triangles is class 2. However, all hyperplanes are not optimal. Optimality of hyperplane is determined by maximum margin for classification that can be obtained.

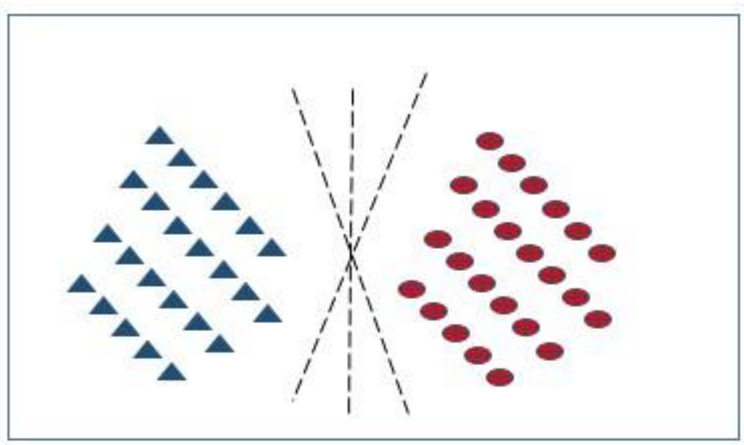


Figure 2-12 Multiple Hyperplanes Separating Two Classes of Data (Dezyre, 2018)

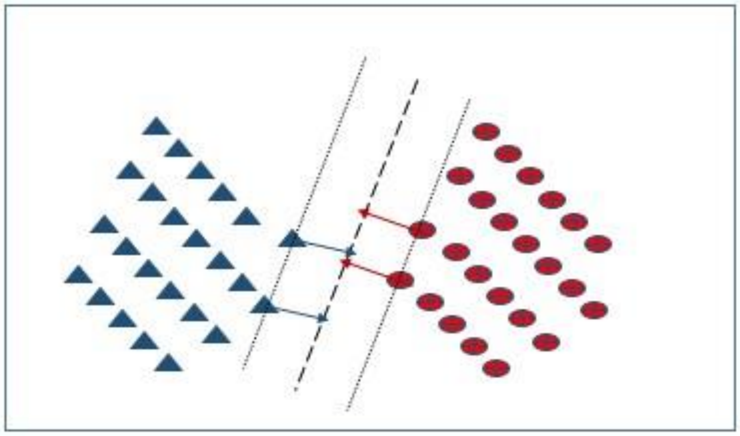


Figure 2-13 Maximum Margin Classifier (Dezyre, 2018)

Figure 2.14 shows Maximum Margin Classifiers (MMC). MMC is an optimal solution from a given set of possible solutions for classification. We have two classes in the classifier, red coloured circles is class 1 and blue coloured triangles is class 2. Objective of the MMC is to choose the hyperplane which is farthest from the classified objects. The solution hyperplane, which is centre dotted line in Figure 2.14, has the maximum width slab for MMC. The dots and triangles lying on the edge of the slab is called Support Vector Machines (SVM). There are two types of SVM classifiers namely hard margin classifier and soft margin classifiers. Hard margin classifiers are used for linearly separable dataset and soft margin classifiers are used for linearly inseparable datasets. Fundamental theoretical element of SVM is hyperplane. As given in (T. Hastie, 2009) the hyperplane can be defined as:

$$f(x) = \beta_0 + \beta^T x \tag{2.3}$$

Where f(x) is a hyperplane, β is the weight vector, β^T is transpose of weight vector and β_0 is the bias and x is training example closest to hyper plane. The optimal hyper plane can be further represented as,

$$|\beta_0 + \beta^T x| = 1 \tag{2.4}$$

Training example closet to hyper plane is called support vectors. One can arrive at the distance measure between support vectors x and the hyper planes [β, β_0] as:

$$distance = \frac{|\beta^T x + \beta_0|}{||\beta||} \tag{2.5}$$

In a canonical hyper plane, the numerator in Equation (2.5) will be 1 and hence the distance of support vectors to hyper plane will be given by

$$distance_{support\ vector} = \frac{1}{||\beta||} \tag{2.6}$$

Maximizing the margin of error implies minimizing the Lagrangian as given by Equation (2.7).

$$\min_{\beta,\beta_0} L(\beta) = \frac{1}{2}||\beta||^2 \ constrained\ by\ y_i(\beta_0 + \beta^T x) \geq 1 \forall i \tag{2.7}$$

Where y_i denotes labels of training batches. By solving Lagrangian optimization using Lagrangian multiplier, weight vector β and bias β_0 can be obtained which in turn provide optimal hyper plane and thus support vectors.

Figure 2.14 shows two different types of kernels namely linear and Radial Basis Function (RBF). SVC on linear kernels are used for linearly separable classes. RBF kernels are used for linearly inseparable classes.

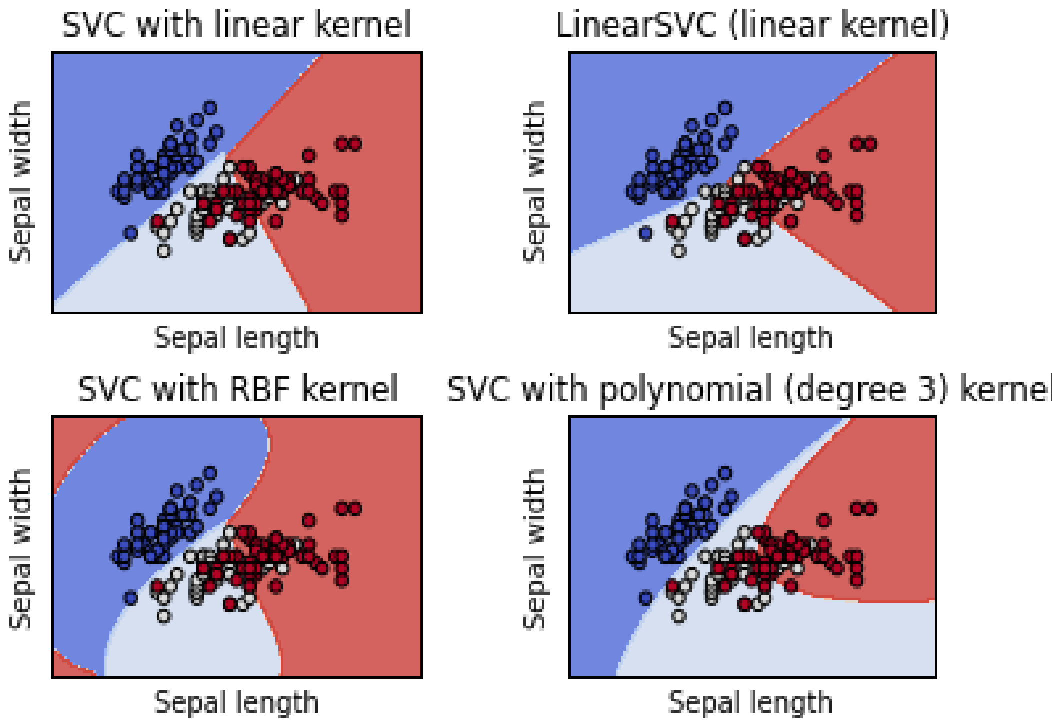


Figure 2-14 Various SVM Kernels Used for Classification Using Sklearn Package on Iris Dataset of Facial Images (Python Code Output)

Basic premise of machine learning is to train the classifier on test dataset to generalize for unseen/unknown datasets. This is called principle of induction learning.

Figure 2.15 shows steps involved in SVM classifier. Primary training dataset is defined for a given classification problem. Depending the dataset, suitable SVM kernel is selected. For linearly separable datasets, the linear kernels shown in the Figure 2.14 are selected. For datasets which are not linearly separable, RBF kernels are used. The training data is then fed to obtain Support vectors and check for errors and hinge loss in case of RBF kernel.

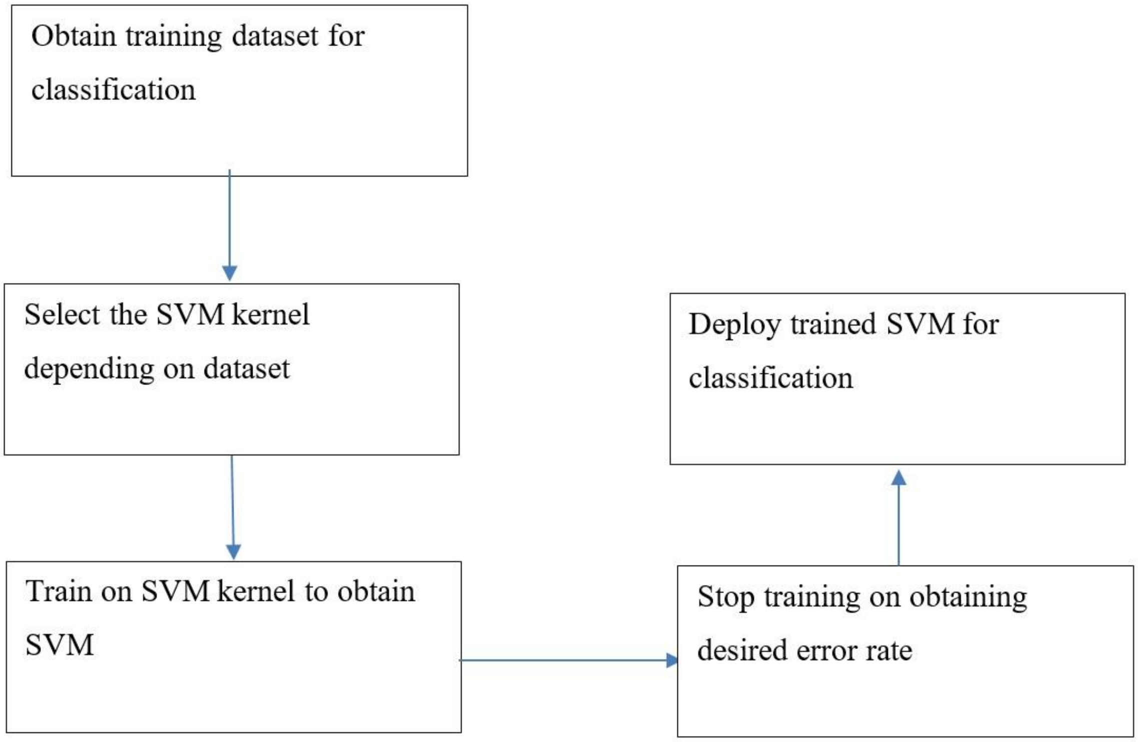


Figure 2-15 Training and Deployment of SVM Classifier

As hinge loss reduces below acceptable threshold, training is stopped and obtained SVM is used for classification application.

2.6 Optimization Techniques and Stochastic Gradient Descent

Optimization problem is one of the oldest problems, which laid the foundation of modern mathematics. It is also widely used in engineering to solve various practical problems. In this research, optimization is used to solve for spectrum efficiency in the form of Q_{spec}. Among many techniques in optimization, Stochastic Gradient Descent (SGD) is used in this research extensively. SGD optimization method is for minimizing objective function that is expressed as a sum of differential functions.

In machine learning and optimization problems, minimizing objective function will be of the form

$$Q(w) = \frac{1}{n}\sum_{i=1}^{n} Q_i(w) \tag{2.8}$$

As given in Equation (2.8), w is the parameter that is estimated to minimise objective function Q(w). Q_i is observed in i^{th} training set. Each SGD performs the following operation:

$$\omega = \omega - \eta \sum_{i=1}^{n} \nabla \,{Q_i(\omega)}/{n} \tag{2.9}$$

Equation (2.9) indicates the way the SGD algorithm works to update the parameter ω to minimize the objective function or loss function. In Equation (2.9), η is the step size or learning rate, ω is the parameter to be estimated to minimize the loss function and n is the number of dataset in the training sample. But for each training set the following update is incorporated.

$$\omega = \omega - \eta \nabla Q_i(\omega) \tag{2.10}$$

At the end of ‘n’ dataset in training, most optimal value of ω is obtained. SGD is a simple and effective approach for machine learning. It is applied in SVM, logistic regression and deep learning with back propagation. SGD classifier from python library sklearn is used for further application of SGD in various steps in this research. Further SGD Classifier supports various loss functions. “Hinge” loss function is used for SVM based solution. Apart from two class classification, SGD can be used in multiclass classification problems also. In spectrum sensing, one can formulate detection of spectrum hole as two classes that is hard detection problem with only two possible states; presence or absence of PU. Further detection problem can be formulated as multi class detection with addition of frequency, time and space variables for spectrum resources. Figure 2.16 shows example of multiclass SGD classifier with 3 classes: setosa, versicolor and virginica. Multiclass SGD is used to approximately classify these classes with a degree of error as shown in Figure 2.16.

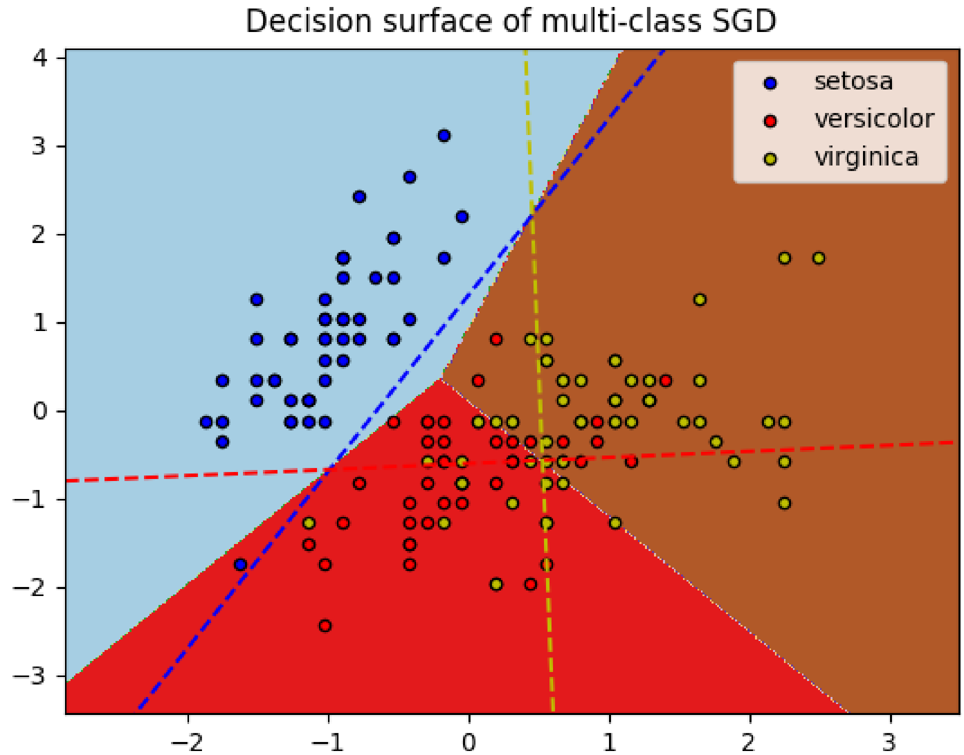


Figure 2-16 Multiclass Classification With SGD (Python Code Output)

2.7 Summary

A brief overview of many concepts and techniques required for essential grasp of the research topic of this thesis is presented in this chapter. Further, most of these techniques and concepts will be further elaborated and referenced in the later chapters of this thesis. Notably Stochastic processes, detection theory, network theory of MANET and heterogeneous networks, various spectrum sensing techniques and SVM will have requisite additional details in the subsequent chapters of the thesis. The diversity in the nature of the topics and concepts reviewed in this chapter offers an overview of multi-disciplinary aspect of the research studies presented in this thesis.

Chapter 3 - Higher Spectrum Efficiency Using Cognitive Radio

This chapter aims at highlighting the importance and the significance of CR for the improvement of spectral efficiency of a communication system. This chapter also proposes a need for a modification to the prevalent concept of spectral efficiency. A new definition termed effective spectral efficiency has been introduced and its distinction relative to conventional spectrum efficiency is also highlighted. This chapter also presents a discussion on the concept of CR on heterogeneous networks and the rationale for it in the context of need for the enhanced spectral efficiency. The focus of this chapter is on single node-based spectrum sensing (1-D spectrum sensing). The associated inherent drawbacks of 1-D spectrum sensing are also discussed in this chapter.

3.1 Need for Higher Spectrum Efficiency and Introduction to Spectrum Sensing Based Cognitive Radio

Spectral efficiency is a measure of amount of information that can be sent on wireless resources (time, frequency, space). It is measured in bits/s/Hz at a point in space. Increase in deployment of wireless devices has given rise to a need to have higher spectral efficiency. Traditional network techniques like cell-based network design have met increased spectral efficiency need of cellular voice and data human type communication so far. Further CDMA (2G/3G) and OFDMA (4G) have facilitated improved modulation and transmission techniques. In future with the deployment of Internet of Things (IoT), billions of machine type communication devices will be in operation using wireless infrastructure.

Traditional network structure based techniques such as WLAN, Pico Cells and many error corrections codes like Turbo codes and LDPC, may approach physical limits. Therefore, special techniques are needed to facilitate the wireless devices with the feature of intelligent usage of spectrum. Review of existing literature suggests there is a vastness of spectrum holes spreading across, time, frequency and space (S. Haykin, 2006). To exploit this vacant spectrum there is a need to sense the unused spectrum and use it for appropriate wireless communication applications. Research studies reported in (S. Haykin, 2006), (Joseph Mitola III, 2000), (S. Haykin, 2005), (M.A. McHenry, 2005), (M.A. McHenry, 2006) (Jantti, R., 2011) and (SiXing Yin, 2012) clearly show the prevalence of abundant unused spectrum, which can be utilised using the concept of spectrum agility. True sense of spectral efficiency should be redefined by considering effective spectrum efficiency, which can be defined as:

$$Effective\ Spectral\ \ efficiency\ = \frac{\frac{\frac{bits}{sec}}{Hz} * spectrum\ used}{Total\ spectrum\ avaiable} \qquad (3.1)$$

Equation (3.1) will be used to evaluate the improvement in spectral efficiency in this research. This is also a new definition which has been introduced to the field of wireless communication and is a novel contribution to the field. First term of the RHS of Equation (3.1) comprising bits/sec/Hz has been used extensively in past century of wireless research to achieve better throughput for a given wireless channel. Current scientific community defines this as channel spectrum efficiency. Effective spectral efficiency definition goes further to account for efficiency in spectrum utilization in addition to channel spectrum efficiency.

In Equation (3.1), it is necessary to note that the definition of total spectrum available in the denominator depends on numerous factors like network architecture, transmit power required, range of transmission and frequency of transmission. One can reach maximum spectral efficiency for a given network provided if the spectrum used equals the total spectrum available. The aim of this thesis is to device methods and propose technology to achieve this theoretical limit for any network architecture. The same definition can be used to determine the optimal network topology to maximize the total spectrum available and hence increase the effective spectral efficiency. In this research, effective spectrum efficiency will be analysed extensively with respect to MANET and MANET overlaid on heterogeneous network.

Basic premise to increase spectral efficiency by increasing available spectrum is through spectrum agility. Spectrum agility is achieved through cognition in licensed spectrum usage, when it is not used by licensed user or for the main purpose of usage from operator like for telecommunication. For example, according to (Jantti R., 2011), to use white space (the spectrum hole in 700 MHz TV transmission), secondary user must avoid interference with TV broadcast. Another example and subject matter of this research is to use medium to longer range communication resources used by cellular communication (Space, Time and Frequency) by short range protocols used in technologies like MANET. Example for this type of usage is the utilisation of cellular 2G, 3G, and 4G spectrums by a Bluetooth, Wi-Fi direct or LTE direct. Cellular spectrum usage is for longer distance and is transmitted with higher power. MANET/D2D communication is for shorter distance and can use lower transmit power. But when such spectrum agile systems are desired to be designed, one should design them in such a way that primary usage is not affected. In this research, such classes of spectrum agile systems are proposed, where by using spectral agility, one can increase the availability of spectrum bands for MANET communication to achieve improved spectral efficiency.

3.2 Cognitive Radio (CR) System Model

This section presents a system model for CR with single node spectrum sensor. Figure 3.1 shows CR system. CR system consists of a communication system which uses licensed band and the device that uses licensed spectrum is called the PU. Example of such system is 2G, 3G, 4G cellular mobile devices, which are supported by cellular infrastructure for communication. Further, a CR system consists of secondary user or CR user, who does not use licensed spectrum when PU uses it. CR user checks the usage of licensed spectrum by

PU. If it is not occupied by the PU, CR user tries to use the unused licensed spectrum. CR user also continues to monitor the PU signal in the spectrum it is using. If it detects signals from PU, it vacates the licensed spectrum. PU signals can be detected by the quantification of transmitted power, which is specified by cellular standards. PU or licensed user will always have the priority over spectrum usage.

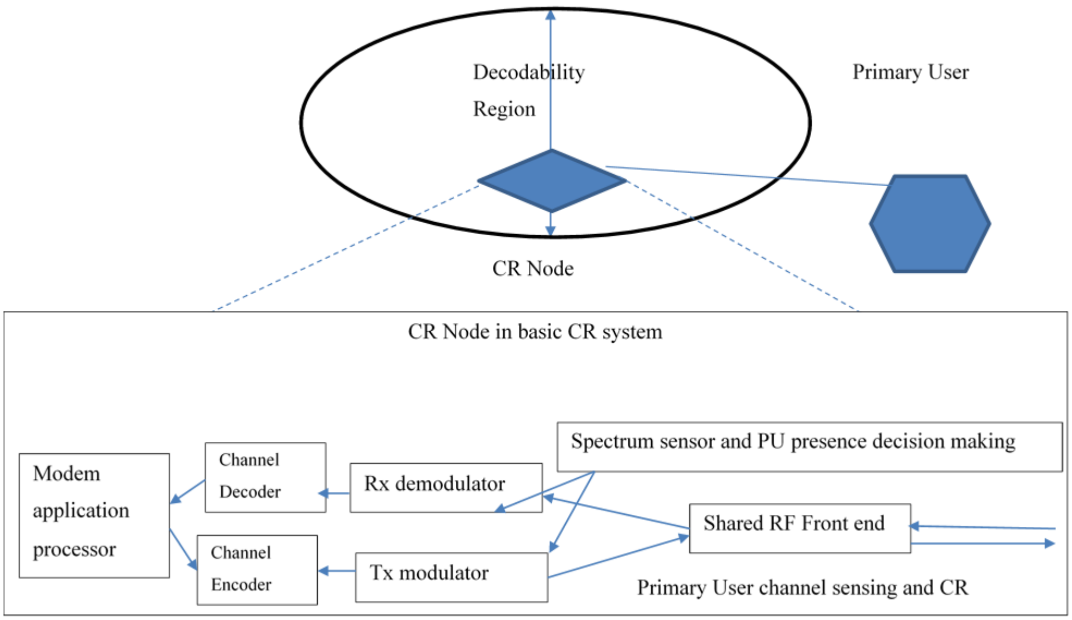


Figure 3-1 Cognitive Radio System Model with Single Node Spectrum Sensor

Typical spectrum sensor referred in (Zhi Quan, 2007), (Anh Tuan Hoang, 2007), (Anh Hoang, 2010), (Chen Guo, 2009), (Y. H. Zeng, 2009), (Javed, F, 2010) and (Tingting Liu, 2010) has implemented basic spectrum sensing algorithms either in its hardware or software. There are many ways to detect the presence of PU through spectrum sensing. There is a basic energy-based spectrum sensing to waveform-based spectrum sensing as given in (Wei Zhang, 2009).

Following are the few methods used to detect the presence of PU using spectrum sensing:

- Matched Filtering
- Energy Detector
- Spectral Correlation (Cyclo-stationary)
- Radio Identification Based Sensing
- Waveform Based Sensing
- Multi-Dimensional Spectrum Sensing

Energy detector has been considered in describing the system model of Figure 3.1, although many other algorithms listed here have advantages over energy detectors in terms of accuracy and robustness. For initial description and throughout this thesis, energy detectors are in consideration. The aim of this thesis is to build around network architecture to achieve improved spectral efficiency and not improve standalone spectrum sensing algorithm. This thesis proposes a novel method to improve spectrum sensing system performance, by combining many of these energy based spectrum sensors.

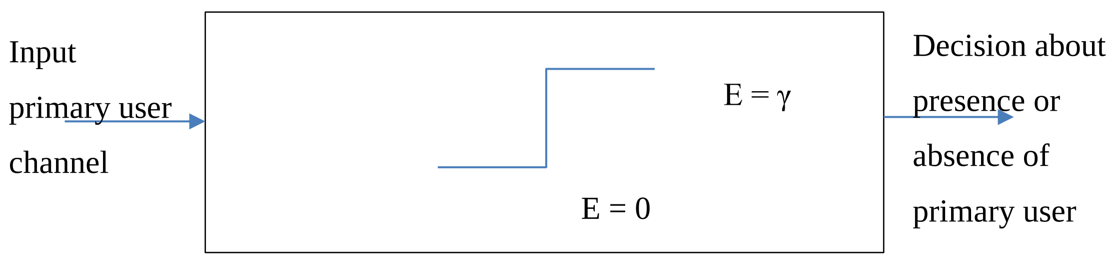


Figure 3-2 Energy Threshold Based Spectrum Sensor

Figure 3.2 shows simple energy detector, which polls or senses PU channel and evaluates its energy with respect to threshold γ. If the energy of the channel equals or exceeds γ, spectrum sensor decides that channel is occupied by the PU. If the energy is below the threshold γ, then sensor decides on absence of the PU.

System model for basic energy detector based CR system can be represented following the approach stated in (Wei Zhang, 2009) by considering the following hypothesis:

H0: Primary user is absent
H1: Primary user is in operation

Considering spectrum sensing at only one CR node and assuming the sensing channel is Additive White Gaussian Noise (AWGN) channel, one can map the hypothesis as follows:

$$x_i(\mathrm{t}) = \begin{cases} w_i(t), & H0 \\ h_i(t)s(t) + w_i(t), & H1 \end{cases} \tag{3.2}$$

Where $w_i(t)$ is the AWGN noise, $h_i(t)$ is channel impulse response and s(t) is the transmitted signal from PU. Energy of the signal x_i(t) is given by:

$$\xi = \int x_i^2\,(t)dt \tag{3.3}$$

Where ξ, is energy contained in the PU communication channel. Energy detection based spectrum sensor, compares this received energy with predefined threshold γ, to decide on one of the two hypotheses H0 or H1. Performance of the sensor is directly determined by its ability to detect PU correctly. Performance of energy detection-based spectrum sensor can be measured by following parameters:

1. Probability of missed detection (which directly results in interference to PU)
2. Probability of false alarm (which results in decreased opportunity to exploit the available bandwidth)
3. Sensing time (Actual time required to decide on the presence of PU)
4. Switching time (Time taken to switch from and to the licensed spectrum)

5. Outage probability (Probability that no signal can be detected or transmitted in a licensed channel)
6. Bit Error Rate (BER) of the licensed channel

Assuming AWGN channel, as given in (Wei Zhang, 2009), above performance measures can be calculated by the following formulae.

Probability of false alarm is given by:

$$\mathrm{Pf,i} = \frac{\Gamma(u, \frac{\lambda i}{2})}{\Gamma(u)} \tag{3.4}$$

Probability of detection is given by:

$$\mathrm{Pd,i} = Q_u(\sqrt{2\gamma_{i,}}, \sqrt{\lambda_i}) \tag{3.5}$$

Probability of missed detection is given by:

$$\mathrm{Pm,i} = 1 - \mathrm{Pd,i} \tag{3.6}$$

Definitions of symbols used in Equations (3.4), (3.5) and (3.6) are as follows; u is the time bandwidth product of the energy detector. Γ (a, x) is incomplete gamma function and Q_u (a, b) is generalized Marcum Q function. λ_i is energy detection threshold of i^{th} CR. Here only one CR is considered. γ_i is the instantaneous SNR of i^{th} CR spectrum sensing channel.

(Stotas S., 2011) analyses relation between optimum sensing time and power allocation in CR. He also discusses the relation between sensing time and power allocation in wideband communication. This proves the importance of sensing time in CR systems. (Aluru P, 2010), proposes methods to improve sensing time in CR receivers without considering transmit power. (Hamdi K., 2009) suggests methods to improve throughput of the CR network by decreasing sensing time. Apart from the power allocation and throughput of the network, joint power allocation and false alarm affect the sensing time as discussed in (Myung Sung Jang, 2009), (He Jian, 2010), (Chengshi Zhao, 2010) and (Babadi B., 2008).

Considering the research studies reported in (Tingting Liu, 2010), (Insook Kim, 2010), (Dongmei Shu, 2010) and (Dong Wei, 2010), it is assumed that each of 200 KHz channel, from 20 MHz to 2.5 GHz bands for communication and sensing**.** In these research studies, it is found that more than 50% of Channel Vacation Duration (CVD) of 75 sec can be found.

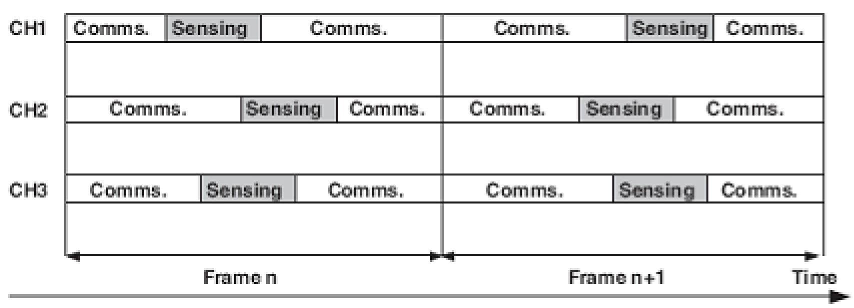


Figure 3-3 Time Slots for Communication and Sensing on the Same Channel

Figure 3.3 depicts time slot for communication and spectrum sensing distributed across the channel, if the same radio receiver is used for both communication and sensing. In case of dedicated sensors, one can eliminate the sensing time slot required in the air interface frame structure in a single spectrum sensor architecture. However, if there are multiple sensors with co-operative architecture, this may not be possible. Sensing time of the standalone spectrum sensor will be equal to processing time for single attempt decision. However, if standalone sensor takes ‘N’ time slots to detect the PU, then sensing time is given by:

$$\text{TS} = \frac{\tau}{\gamma^2}(Q^{-1}(P_f) - Q^{-1}(P_d)\sqrt{2\gamma + 1})^2 \tag{3.7}$$

Where,

P_f is the probability of false detection of single detector

P_d is the probability of correct detection of single detector

γ is detection threshold

τ is the channel sampling interval of the channel

Q^{-1} is an inverse Q function

Another important measure in CR system is the time taken to switch between channels. This is called switching time. Channel switching time is the total time to sense PU and switch in or switch out of PU channel

Channel switching time = Channel sensing time + time to process actual frequency switch.

In a typical 3 GPP communication system, time to switch channels will be around 1 frame duration. With a maximum frame duration is 25 ms (current standard supports 10 or 5 ms as well), channel switching time is given by

$$\text{Channel switching time} = \text{Channel sensing time} + 25\text{ ms} \tag{3.8}$$

BER of the channel is dependent on the modulation schemes. For QPSK module scheme, BER is given by

$$\text{BER} = \frac{1}{2}erfc(\sqrt{E_b/N}) \tag{3.9}$$

Where E_b is energy of the signal and N is the channel noise

In addition to BER, channel outage probability is a very important measure to show that, chances of outage of CR system is very low. The channel outage probability is given by

$$\text{Pout} = P[\Gamma < \Gamma_t] \tag{3.10}$$

Where Γ is the SINR at present and Γ_t is the SINR at time t, which is the threshold below which signal cannot be detected. Equation (3.10) for the outage probability is very general since SINR depends on the network structure, type of air interfaces and propagation model used. Typical thresholds for different communication systems are as shown in Figure 3.4. The receiver noise floor is around -100 dBm, below which signal cannot be detected. This is a very important measure, which suggests physical limits of the receiver to detect the presence of PU. Outage probability of the sensing channel is closely related to receiver sensitivity and the SINR of the channel.

RAN Technology		GSM	HSPA	LTE
Data rate (kbps)		**12.2**	**1200**	**6400**
Transmitter – UE				
A	Max. TX power (dBm)	33	23	23
B	TX antenna gain (dBi)	0	0	0
C	Body loss (dB)	3	0	0
D	EIRP (dBm)	30	23	23
Receiver – BTS/Node B/eNode B				
E	Node B noise figure (dB)	-	2	2
F	Thermal noise (dBm)	-	-108.2	-118.4
G	Receiver noise floor (dBm)	-	-106.2	-116.4
H	SINR (dB)	-	-17.3	-7
I	Receiver sensitivity (dBm)	-114	-123.4	-123.4
J	Interference Margin (dB)	0	3	1
K	Cable Loss (dB)	0	0	0
L	RX antenna gain (dBi)	18	18	18
M	Fast fade margin (dB)	0	1.8	0
N	Soft handover gain (dB)	0	2	0
Maximum path loss		**162**	**161.6**	**163.4**

Figure 3-4 Typical Transmitter and Receiver Power Characteristic of Different Radio Access Networks (RAN)

3.2.1 Effective Spectrum Efficiency of Standalone Network and Network with CR Function

In this subsection, spectral efficiency of different communication systems is discussed. Table 3.1 depicts the spectral efficiency of various wireless communication system.

Table 3-1 Spectral Efficiency of Various Wireless Communication Systems

Service	Standard	Year Launched	Max. net bitrate *R* per carrier per one spatial stream (Mbit/s)	Bandwidth B per carrier (MHz)	Max. link spectral efficiency *R/B* ((bit/s)/Hz)	System Spectral efficiency (bits/sec/Hz)
1G cellular	NMT 450 modem	1981	0.0012	0.025	0.45	0.064
1G cellular	AMPS modem	1983	0.0003[2]	0.030	0.001	0.0015
2G cellular	GSM	1991	0.013 × 8 timeslots = 0.104	0.2	0.52	0.17(in 1999)
2G cellular	D-AMPS	1991	0.013 × 3 timeslots = 0.039	0.030	1.3	0.45(in 1999)
2.75G cellular	CDMA2000 1× voice	2000	0.0096 per phone call × 22 calls	1.2288	0.0078 per call	0.172 (fully loaded)
2.75G cellular	GSM + EDGE	2003	0.384 (typ. 0.20)	0.2	1.92 (typ. 1.00)	0.33
2.75G cellular	IS-136HS + EDGE		0.384 (typ. 0.27)	0.200	1.92 (typ. 1.35)	0.45
3G cellular	WCDMA FDD	2001	0.384	5	0.077	0.51
3G cellular	CDMA2000 1x PD	2002	0.153	1.2288	0.125	0.1720 (fully loaded)
3G cellular	CDMA2000 1×EV-DO Rev.A	2002	3.072	1.2288	2.5	1.3
Fixed WiMAX	IEEE 802.16d	2004	96	20	4.8	1.2
3.5G cellular	HSDPA	2007	21.1	5	4.22	4.22
4G MBWA	iBurst HC-SDMA	2005	3.9	0.625	7.23	7.23
4G cellular	LTE	2009	81.6	20	4.08	16.32
4G cellular	LTE-Advanced	2013	75	20	3.75	30

The studies reported in (E.T. Docket No. 10-237, FCC) and (SiXing Yin, 2012) reveal that about 30 to 50% of spectrum is unused across space, time and frequency. So effective spectral efficiency considering link spectrum efficiency is:

$$\text{Effective spectrum efficiency} = \frac{used\ spectrum * link\ spectrum\ efficiency}{Total\ available\ spectrum} \tag{3.11}$$

Since the ratio of $\frac{used\ spectrum}{Total\ available\ spectrum}$ is about 0.5 to 0.7, the overall system spectrum efficiency is always less than link spectrum efficiency. Exceptions are system like LTE-A and LTE, where MIMO facilitates the increase in spectral efficiency. Even in these systems further improvement can be achieved through spectrum sensing. With ever increasing need for bandwidth, there is an ample scope to exploit unused spectrum even in highly spectral efficient system like LTE-A

Considering the case of single energy detection based spectrum sensing accessing 200 KHz channel width and 74 sec channel slots, one can get the following spectral efficiency improvement. Since energy detector is not ideal, it cannot exploit all CVDs. So, the total effective spectrum efficiency with single energy detector is given by

$$\text{Total effective spectrum efficiency} = \frac{(Pd*BWused*Seff)}{BW_T} \quad \text{bits/Sec/Hz} \tag{3.12}$$

Where,

P_d is the probability of detection of standalone energy detector

BW_{used} is the available bandwidth for standalone energy detector

S_{eff} is the standalone spectrum efficiency of the air interface

BW_T is the total available bandwidth across the primary network

For a network with 1000 channels which is using only one channel with a bandwidth of 200 KHz and with single sensor spectrum sensing scheme, total effective spectrum efficiency with single channel spectrum sensor is given by:

$$= \frac{(Pd*0.7*1001*16)}{1000} \text{ bits/Sec/Hz}$$

Efficiency improvement over without using spectrum sensing CR is given by:

$$=1- \frac{(Pd*0.7*1001*16)}{Pd*0.7*1000*16} *100 = 0.1\%$$

One can see an improvement in spectral efficiency by using single channel and single detector is negligible. Key to improving the spectral efficiency is to deploy many energy spectrum sensors and try to use as many idle channels as possible. In Equation (3.12), higher the P_d, better is the effective spectral efficiency of the network. Improvements of P_d with constraints on P_f as used in (Dong Wei, 2010), (Rong Cong, 2010), (Y. H. Zeng, 2009) may have diminishing rate of return, if actual usable bandwidth is not increased.

3.3 Application of Spectrum Sensing Based CR in MANET and Heterogeneous Networks

There is a great need to enhance spectral efficiency in next generation broadband networks and IoT. Next generation broadband networks will have heterogeneous air interfaces and support many types of interfaces as per application needs. Heterogeneous networks can exceed the spectral efficiency of homogenous networks as demonstrated by using relays, Femtocells and LTE direct. However, they can provide better services and value to the end user by using spectrum sensing based CR capability in their short-range interface.

IoT networks can be used to acquire, process and transmit data by machines. One of their interfaces can be connected to internet and others can be used to communicate with each other directly, by forming MANET. (Mingrui Zou, 2008), (Serrador A., 2008), (Guangquan Chen, 2008) and (Zhang Jin-bao, 2007) discuss aspects of different heterogeneous networking, including self-organization, mobility and network management. (Ghosh, R, 2010), discusses different structure of heterogeneous networks. (Khandekar A., 2010) discusses the heterogeneity of network architecture in LTE-A. (Tang and Long Chi, 2010) deals with deployment of Cognition at network level in a heterogeneous network. (Xuebing Pei, 2010) suggests various ways to manage radio resources in heterogeneous networks to increase the spectral efficiency. This infers that there is a need to go beyond LTE-A to efficiently use the heterogeneous resources.

Typical heterogeneous network as described in LTE-A is given in Figure 3.5. As can be seen in Figure 3.5, there are 4 different air interfaces; Base station to Femto cells, Femto cells to mobile device, mobile device to base station and device to device interface. Since transmit power of these interfaces is different, it is highly desirable to have spectrum agility to gain spectral efficiency. Also, the hierarchical nature of network enables deployment of CR. CR enabled interfaces can transmit at lower power with a shorter communication range than cellular interfaces to avoid interference. Therefore, CR deployment in heterogeneous networks is very much feasible.

MANET is infrastructure less network used for device to device communication. They can be single hop or multi-hop MANET. In this research, the focus is on both single hop and multi-hop MANETs for CR deployment. (Fu, 2007) suggests use of CR in MANET within cellular network. (Chin, 2002) discusses different protocols used in MANET. (IETF RFC 2501) proposes basic routing protocol that can be used in MANET. (Chin, 2002) also details various practical experiences in implementing routing protocols in MANET. Routing protocol is very important in MANET implementation. MANETs being on demand or adaptive networks, link establishment and link maintenance are very important.

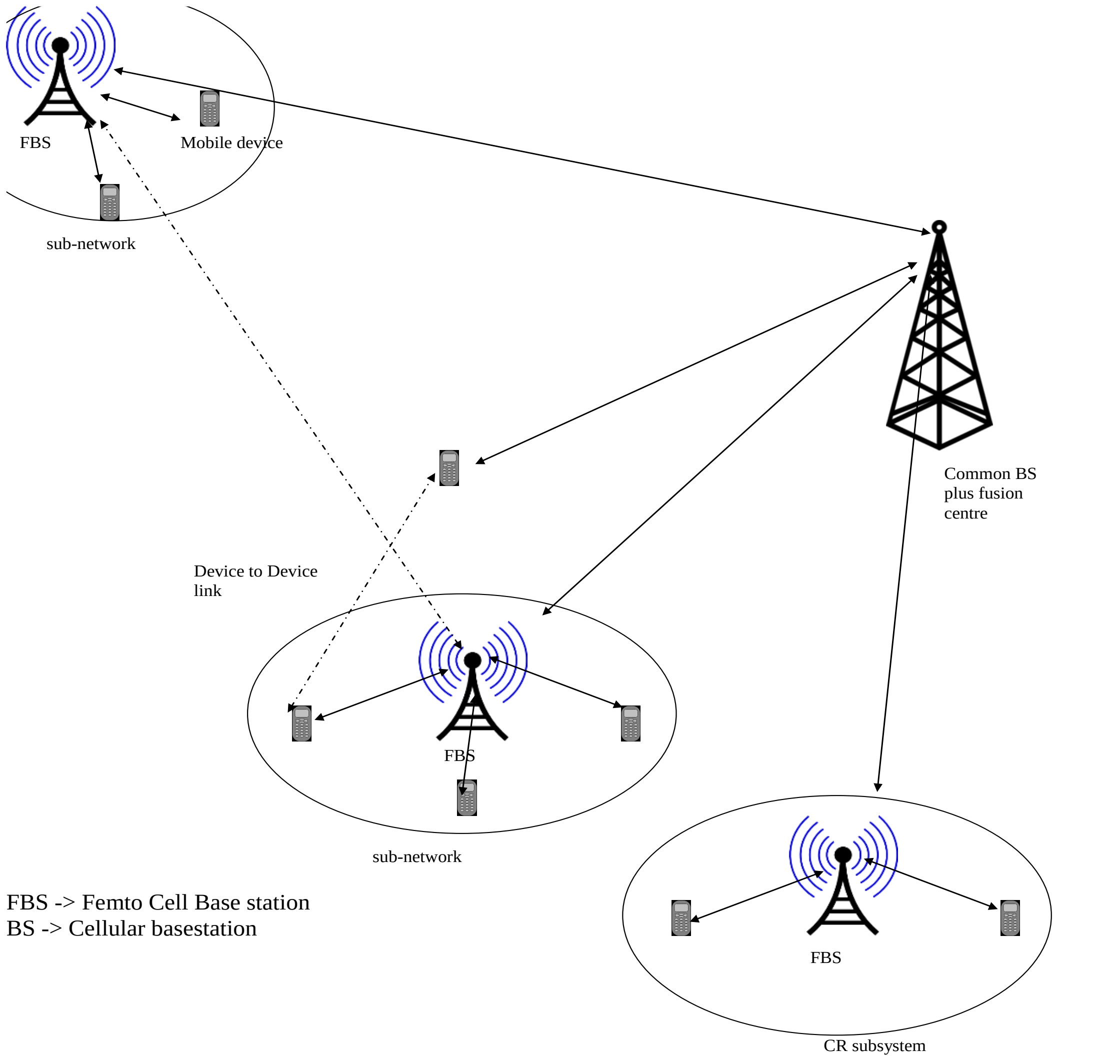


Figure 3-5 Typical Heterogeneous Network, with Multiple Air Interfaces and Multiple Hierarchies of Access Mechanism

Figure 3.6 shows typical MANET, where each mobile device communicates to other without intermediate infrastructure to initiate and maintain communication link. When in multi hop network, the intermediate nodes act like a relay to forward the payload from end node to another intermediate node or to other end node.

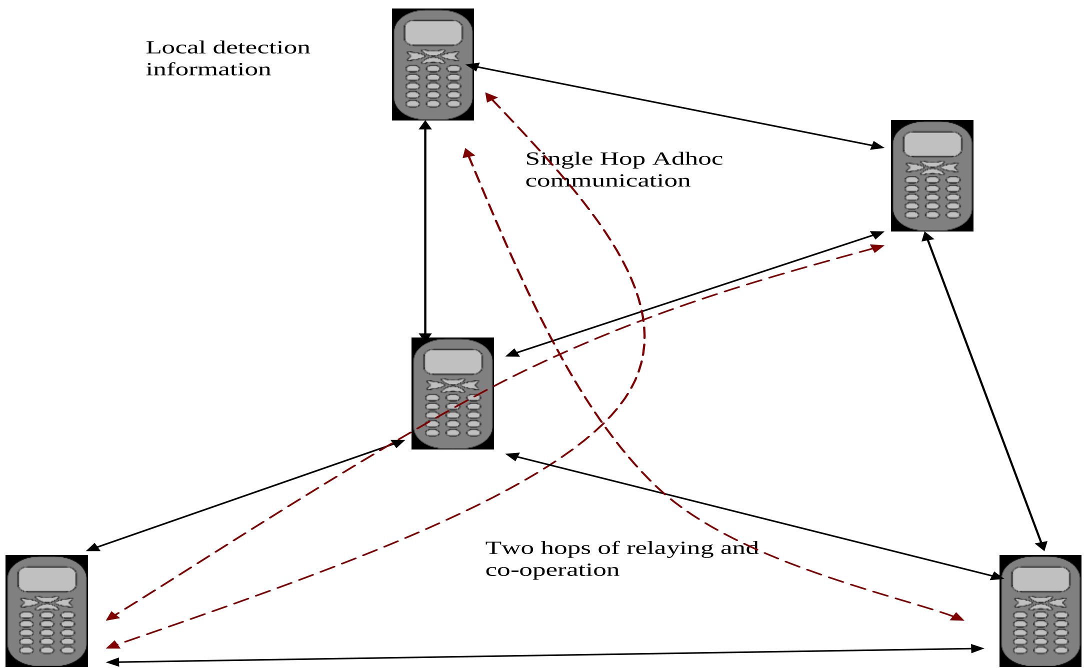


Figure 3-6 Multi-hop MANET

From Table 3.1 and Figure 3.6, there is no physical limitation to implement spectrum sensing algorithms in MANET and heterogeneous networks. Table 3.1 provides receiver and transmitter power requirements, which are very well within limits of CR requirements. Also, sensing time of CR according to Equation (3.7), can be less than the frame duration ranging from 25 ms to 10 ms. Therefore, CR is feasible to be implemented within cellular/heterogeneous network. In MANET given the transmit power which is less than given in Figure 3.4, it should be possible avoid interference to PU. MANET has the advantage of lower transmit power, since it caters to shorter range than the heterogeneous networks. This enables deployment of CR possible in both MANET and heterogeneous networks. However, CR system described in Figure 3.1 has several drawbacks and hence it cannot be deployed in MANET or Heterogeneous networks as it is. There should be changes in the CR system design to enable them to be successfully deployed in MANET and heterogeneous networks, so that the spectral efficiency can be improved by a significant margin. Some of the drawbacks with single spectrum sensor are discussed in the next subsection.

3.4 Summary

This chapter has presented the importance and the significance of CR for the improvement of spectral efficiency of a communication system. A new definition termed effective spectral efficiency has been introduced and its distinction relative to conventional spectrum efficiency has also been presented. The concept of CR on heterogeneous network and the rationale for it in the context of need for the enhanced spectral efficiency are also discussed. The focus of this chapter is on single node-based spectrum sensing. Some of consequent drawbacks are:

1. Single node-based spectrum sensing aims at increasing spectral efficiency by operating on single channel
2. There is no clear means of allocation of channel for spectrum sensing. So, this leads to collision among the CR spectrum sensors
3. Single node spectrum sensors-based CR also suffers from so called "Hidden node Problem", which traditional WLAN also suffers from
4. If more than one channel needs to sense the spectrum hole, then spectrum sensing CR node needs wide band spectrum sensors, which are costlier in terms of hardware and power. This may also make it infeasible to implement in the battery powered devices

Given these shortcomings to operate on multiple channels, spectral efficiency cannot be improved with single node spectrum sensor. Most of the draw backs of single node spectrum sensors are addressed by co-operative spectrum sensing and further by controlled co-operative spectrum sensing. Co-operative spectrum sensing enables application of CR in heterogeneous network and MANET. Controlled co-operative spectrum sensing discussed in the next chapter is one of the key contributions of this thesis.

Chapter 4 - Co-Operative Spectrum Sensing in Heterogeneous Network and MANETs

This chapter aims to address an alternate spectrum sensing technique to overcome the shortcomings of single sensor-based spectrum sensing discussed in chapter 3. It presents the concept of co-operative spectrum sensing suitable for heterogeneous networks and MANET. Single sensor spectrum detection also suffers from hidden node problem that is explained in detail in chapter 2. Machine learning algorithms are able exploit the stationarity in the usage of spectrum. Since spectrum agility is a unconstrained optimization problem, gradient descent plays a vital role is resource allocation. The applicability of gradient descent algorithm for co-operative spectrum sensing in MANET is discussed in this chapter. This chapter proposes a system model for CRMANET, which is again a prominent concept of this thesis for the achievement of enhanced usable bandwidth and improved spectral efficiency.

4.1 Introduction

In co-operative spectrum sensing, each CR node co-operate with each other, by sharing information about detection of presence of PU to each other. However, sharing of information results in communication overhead and results in scalability issues in large network configuration. (Wei Zhang, 2009) and (Dong Wei, 2010) discuss the idea of having a fusion centre, which is centrally located and determines the presence of PU with collective information from CR nodes. (Stotas S., 2011) and (Kandeepan S., 2010) propose various co-operative spectrum sensing schemes. (Mingrui Zou, 2008) suggests relay based co-operative spectrum sensing. Drawback of this system is its latency for DF relays. In this system, one can still use energy threshold-based spectrum sensors to detect the PU at individual node level as described in Figure 4.1.

Figure 4.1 shows the CR nodes in diamond shaped network elements. The fusion centre is located centrally in decodability region denoted through a circular enclosure. The CR node consists of wireless transceiver with RF frontend, which receives the wireless signal from the PU and as well as other nodes. The wireless signal is sent to energy detection for a decision on the presence of PU. The energy detector discussed in chapter 2 is used in this system to detect the PU. The RF front end part of the CR node receives communication from other CR nodes in the co-operative formation. The wireless network is formed as Device to Device (D2D) network between co-operating CR nodes. The communication signals received from the RF front end is sent to channel decoder and demodulator. The CR node also transmits signals to other CR nodes in the co-operative formation.

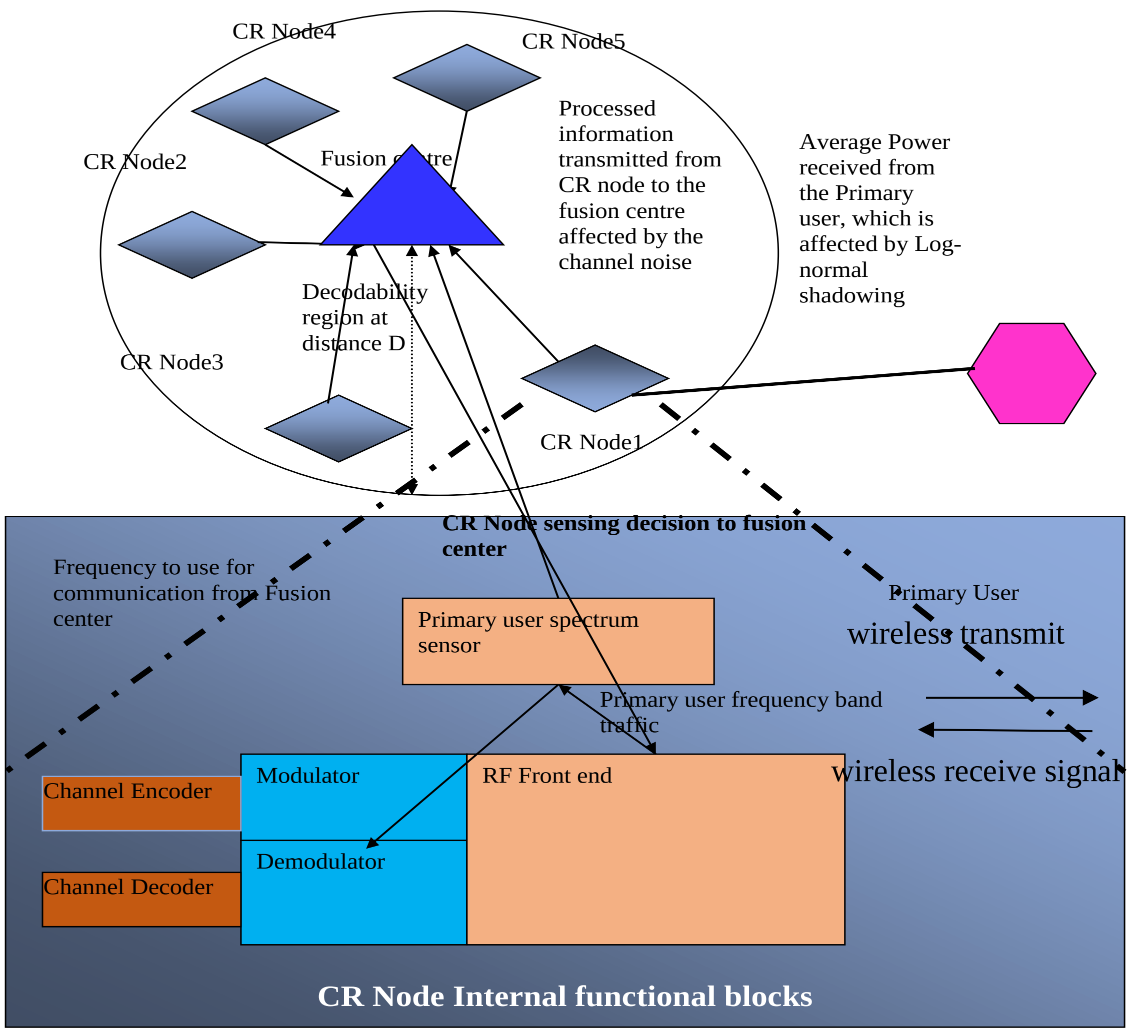


Figure 4-1 Co-operative Spectrum Sensing in Heterogeneous Networks Where Fusion Centre Takes Final Decision About the Primary User Presence

Furthermore, the channel of the PU transmit is being listened to by all CR nodes in co-operative formation. Figure 4.2 shows co-operative spectrum sensing with more than 1 PU. There can also be case where PU uses more than one channel. In the same case, CR node can listen to more than one PU channel.

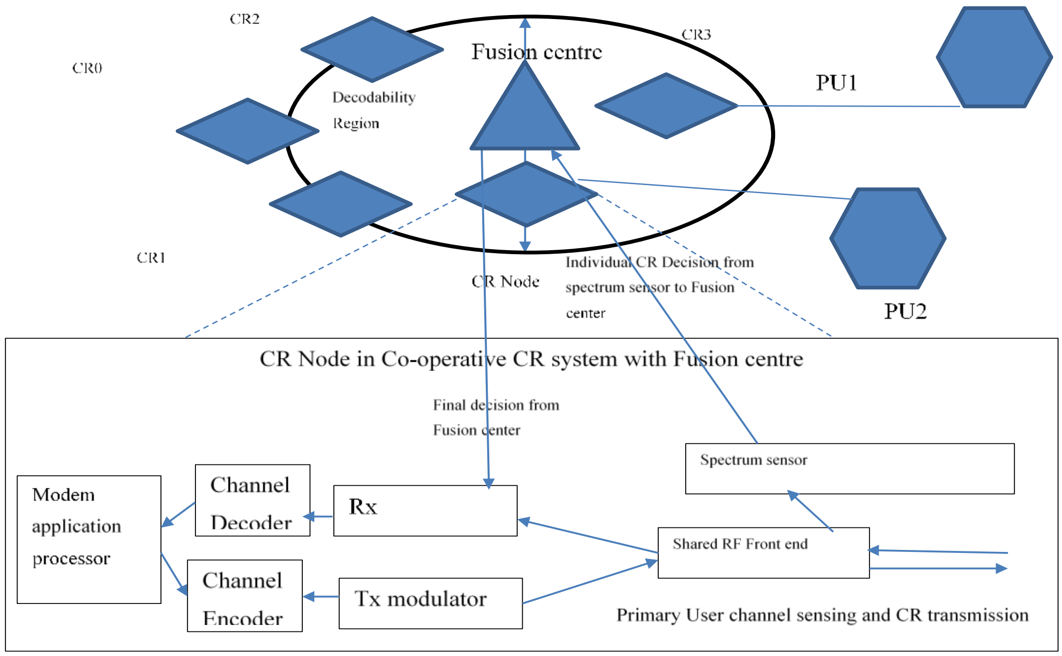


Figure 4-2 Co-operative Spectrum Sensing with Spectrum Sensor in the CR Node

The RF data path for the communication contains the Rx (Receiver) and Tx (transmitter) chains, which are common to conventional RF modem. Apart from conventional RF modem parts, the CR node contains the spectrum sensor, which uses the energy detector as described in Chapter 3.

The PU signal is monitored for the energy in the frequency of interest and presence or absence of PU in a frequency band is reported to the fusion centre and shown in the Figure 4.2. The fusion centre then combines all the CR node information to decide on the presence or absence of the PU. Co-operative spectrum sensing is required to overcome the drawbacks of the single sensor spectrum sensing. Single sensor spectrum sensing suffers from hidden node and fading of sensing channels. Therefore, single sensor-based spectrum sensing system will have higher missed detection rates compared to co-operative spectrum sensors. Decodability region is where co-operative spectrum sensors can detect the PU around the fusion centre. Sensing frequency and CR communication frequency can be the same or can be different. This is because fusion centre can perform the detection of more than one frequency band and assign different frequency for sensing and CR communication. Difference between Figure 4.1 and Figure 4.2 is that, in Figure 4.2, there are more than one PU and Figure 4.1 is for CR system assuming single frequency band and single PU. Most practical deployments involve the latter case of multiband sensing and multiple PUs to be detected at the fusion centre.

4.2 Co-Operative Spectrum Sensing in Heterogeneous Network

The heterogeneous networks are hierarchical networks with support of various types of air interfaces. These networks usually exhibit hierarchy. Therefore, it requires a CR mechanism which is hierarchical. Figure 4.3 depicts the CR enabled heterogeneous network. It has different network elements in the form of Base stations, repeaters, femto cells, mobile terminal and D2D connections. Deployment of these type of networks will occupy more spectrum and spectrum of diverse types. It can be both high quality spectrum like 700 MHz band and unlicensed 5 GHz and 2.5 GHz frequency bands. In heterogeneous networks there can be different types of PUs like PU of Femto Cell Base Station (PUFBS) and Primary User connected to central base station (PUBS). Similarly, CR can be on Femto Cell Base Station (CRFBS) and CR on Central Base station (CRBS). Entire network can be either CR network or PU network. In this case the Femto Cell Base Station (FBS) provides access, sensing and switching CR functions. All the terminals connected to CRFBS will access the high-quality spectrum. Fusion centre will be central base station for small network as shown in Figure 4.3 or it can be hierarchical fusion centre. Having CR sensing at FBS avoids sensing function to be on mobile device, which is battery operated.

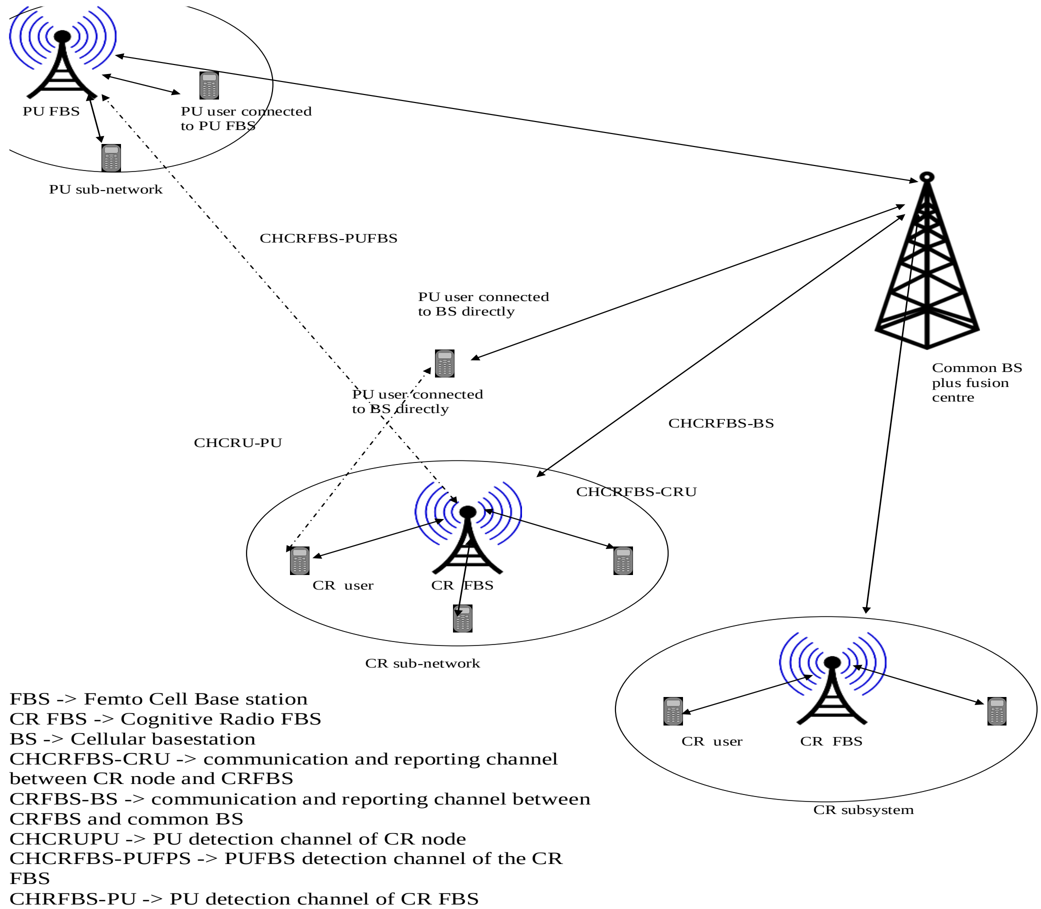


Figure 4-3 CR Enabled Heterogeneous Network

Further channelization is divided into PU and CR channels. As shown in the Figure 4.3, CR has both data and sensing channels as part of wireless network design. PU channel on central base station, which acts as fusion centre will have additional CR fusion channel and CR sensing channel. Co-operative spectrum sensing in heterogeneous networks and hierarchical network can occur at many levels to reduce the probability of existence of hidden nodes to a very small percentage. Apart from having mobile terminal level co-operations, heterogeneous and hierarchical networks can have sub-net level co-operation as shown in the Figure 4.3.

4.3 Co-Operative Spectrum Sensing in MANET

Unlike infrastructure based heterogeneous networks, MANETs have no central fusion centre. They depend on co-operative spectrum sensing at the device level to detect the PU. MANETs will have in-band sensing and co-operation within data channel or communication channel. Each MANET CR node co-operates with other MANET CR node by sending its PU detection information.

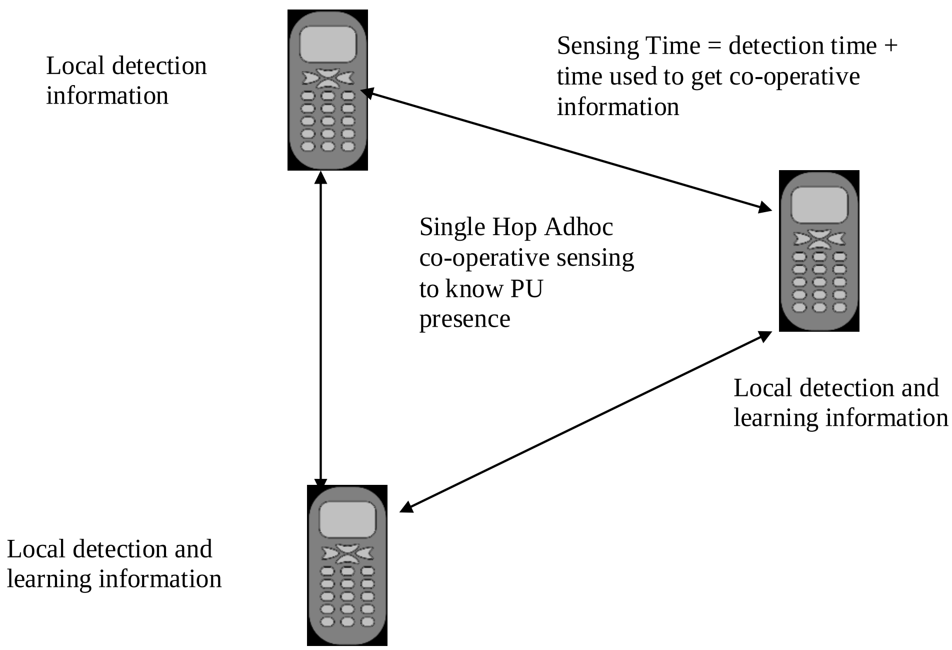


Figure 4-4 Single Hop Co-operative Spectrum Sensing in MANET

Assuming single hop MANET as shown in Figure 4.4, the decision will be made by each node on the presence of PU by combining all the decisions using OR or AND logic. But this will lead to erroneous detection. Both the probability of missed detection and probability of false alarm will be very high compared to acceptable threshold.

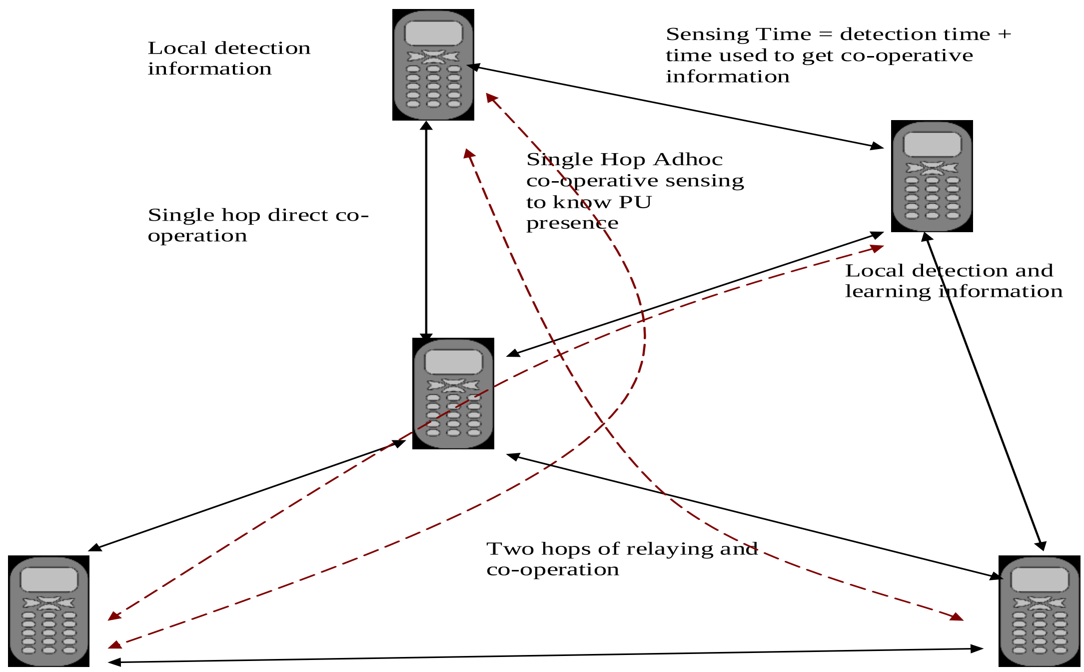


Figure 4-5 Co-operative Spectrum Sensing in Multi-hop MANET

In multi-hop CR network as shown in Figure 4.5, the co-operative information can be forwarded to next hop using Amplify and Forward (AF) or Decode and Forward (DF) relay functions.

4.3.1 Co-operative Spectrum Sensing in MANET using Gradient Descent Algorithm

MANET can be single hop or multi-hop as shown in Figure 4.4 and Figure 4.5, respectively. However, for multi-hop, it is important that number of hops in the network do not increase sensing time. One can assume that the detection takes place at node A (reference node) at time t, node B (next neighbour node) does not detect the PU yet.

Assuming there are N hops, and that Node B is in multi-hop co-operation with Node A, then the total co-operation time is given by:

$$C(\tau) = N*\tau \tag{4.1}$$

Where N is shortest number of possible hops from node nearest to PU to Node which needs to get this co-operative information.

τ is time required to transmit in 1 hop

For a sensing time constraint of $S\tau$, then it should be possible that

$$\mathbf{C(\tau) < S_\tau} \tag{4.2}$$

$$\mathbf{S_\tau > N*\tau} \tag{4.3}$$

This will be the basic equation that determines very fundamental requirement of feasibility of CR in the MANET. As can be seen that, for a constant S_τ, one can include more number of hops, if per hop time τ is lesser. This means that for larger networks with more number of hops (if hop size determines the per hop time), one can have only shallow co-operation of a few hops. For a smaller network with lesser number of hops, one can have deeper co-operation.

Apart from sensing time, major problems to be addressed with CR MANET are:

1. As stated in (Ian F. Akyildiz, 2009), network topology communication over several bands at a time is almost impossible. Because for ordinary MANET, topology communication over single channel using periodic beacon would suffice. But since CR MANET operates on multiple frequency bands, sending beacon on all bands would

be inefficient use of resources. Therefore, there is a need to address this by smart beaconing

2. (Ian F. Akyildiz, 2009) addresses various problems to fully distributed Cognitive Radio Adhoc networks (CRAHNs). It also suggests the energy gradient based co-operative spectrum sensing. For the feasibility analysis, one can consider the gradient based fully distributed scheme simulation to prove the feasibility of CR in MANET
3. Other method is Consensus based Co-operative spectrum sensing in MANET based on the Biological methods. But it is proven in (Ejaz W, 2011) that gradient based method is much superior to consensus-based method, which in turn is superior to AND and OR based resolution in co-operative spectrum sensing
4. Other challenges in the MANET based is network topology that depends on cross-layer design. However the scope of this research is mainly to abstract out of topology and assumes topology that makes it feasible
5. Since the range of CRMANET is very small, it cannot result in the interference to PU. Interference can be reduced using lower transmit power in CRMANET

4.3.2 System Model for CR MANET

In this research for standalone MANET without overlay, the gradient based approach for co-operation is assumed. The approach presented in the research study by (Ejaz, W, 2011) is followed. Gradient based system is defined as follows:

$$\mathrm{x}_n(\mathrm{i}+1) = x_n(\mathrm{i}) - \sum \left[\frac{x_n(i) - x_m(i)}{x_m(i)}\right] \tag{4.4}$$

Where,

xn(i): Energy detected at node n at time i

xm(i): Energy detected at node m and received via co-operation at node n at time i

Gradient based co-operation among the CRMANET nodes does not require the knowledge of the network topology as is required in consensus based schemes. Decision at node n is arrived with energy threshold λ. Binary decision at CR node is made as follows:

$$PU\ detection = \begin{cases} 1, & if \quad x > \lambda \\ 0, & Otherwise \end{cases} \tag{4.5}$$

As given in the Figure 4.6 of single hop MANET, the bidirectional link is established between each neighbour to obtain energy detection information.

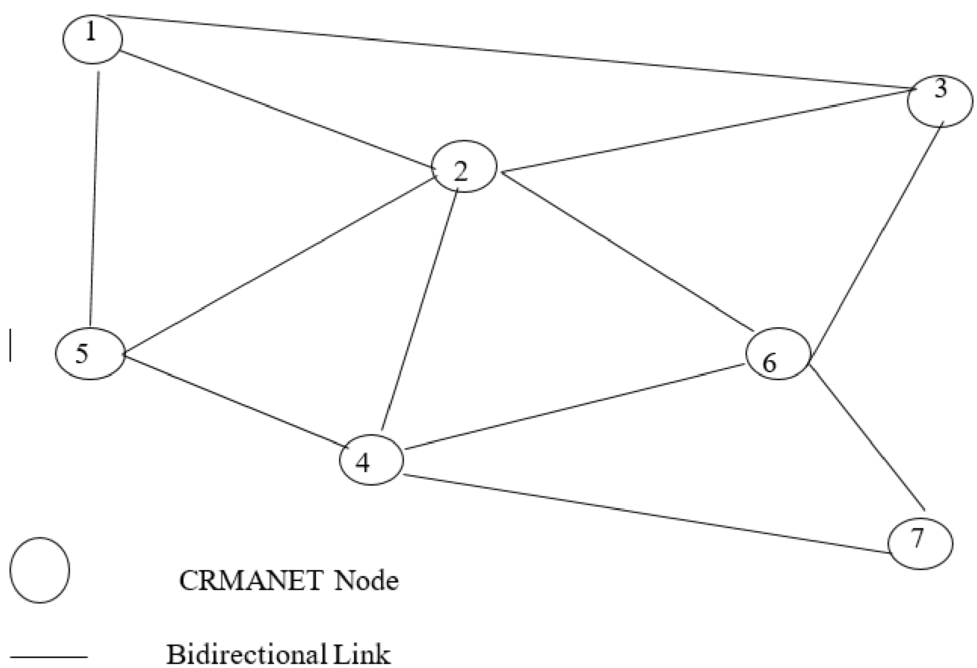


Figure 4-6 Seven Node CRMANET with Nodes in Bidirectional Link Co-operating with Gradient Scheme for PU Detection

In this research, the problem of Spectrum Sensing Data Falsification (SSDF) is not considered. The CRMANET assumes that there is no malicious user and excludes scenario of security breach which has been analysed in (Abhinaba Banerjee, 2014). Assuming CRMANET nodes use energy detector to detect the presence of PU, the system model can be designed as:

$$\mathbf{Y}(\mathbf{r}) = \begin{cases} n(t) \quad H(0) \\ h(t) * x(t) + n(t) H(1) \end{cases} \tag{4.6}$$

Where H(0) is the hypothesis of PU is absent and H(1) is the Hypothesis of PU is present. H(t) is the channel impulse response, x(t) is input signal, y(t) is detector output and n(t) is Additive White Gaussian Noise (AWGN).

The output of energy detector can be modelled as follows:

$$\mathrm{Y} = \begin{cases} \chi^2_{2M} \quad In \quad case \quad of \quad H(0) \\ \chi(2\gamma)^2_{2M} \; In \quad case \quad of \quad H(1) \end{cases} \tag{4.7}$$

Where Y is central Chi-squared and Non-Central Chi squared distributed in case of H (0) and H (1) respectively.

Algorithm for CRMANET using gradient descent can be described using Figure 4.7. The gradient descent algorithm works on signal received by each neighbour, by consecutively eliminating the node with large deviation from mean energy received. List of valid neighbours are updated successively to arrive at the presence or absence of PU. Convergence rate of algorithm as given in (Ian F. Akyildiz, 2009) is quick for smaller number of nodes. But convergence time grows exponentially with substantial number of nodes in the CR network. This will be a major drawback of gradient descent algorithm in

CRMANET. Also, for a large number of nodes, there is a possibility of gradient descent converge to local minima and provides a wrong decision on the detection of presence of PU. Therefore, the system probability and Receiver Operating Characteristic (ROC) curve of CRMANET will be degraded. For smaller sensor network without mobility, gradient descent-based algorithm will be usable. For smaller sensor networks, power required for spectrum sensing will be higher and will be detrimental for real world deployment.

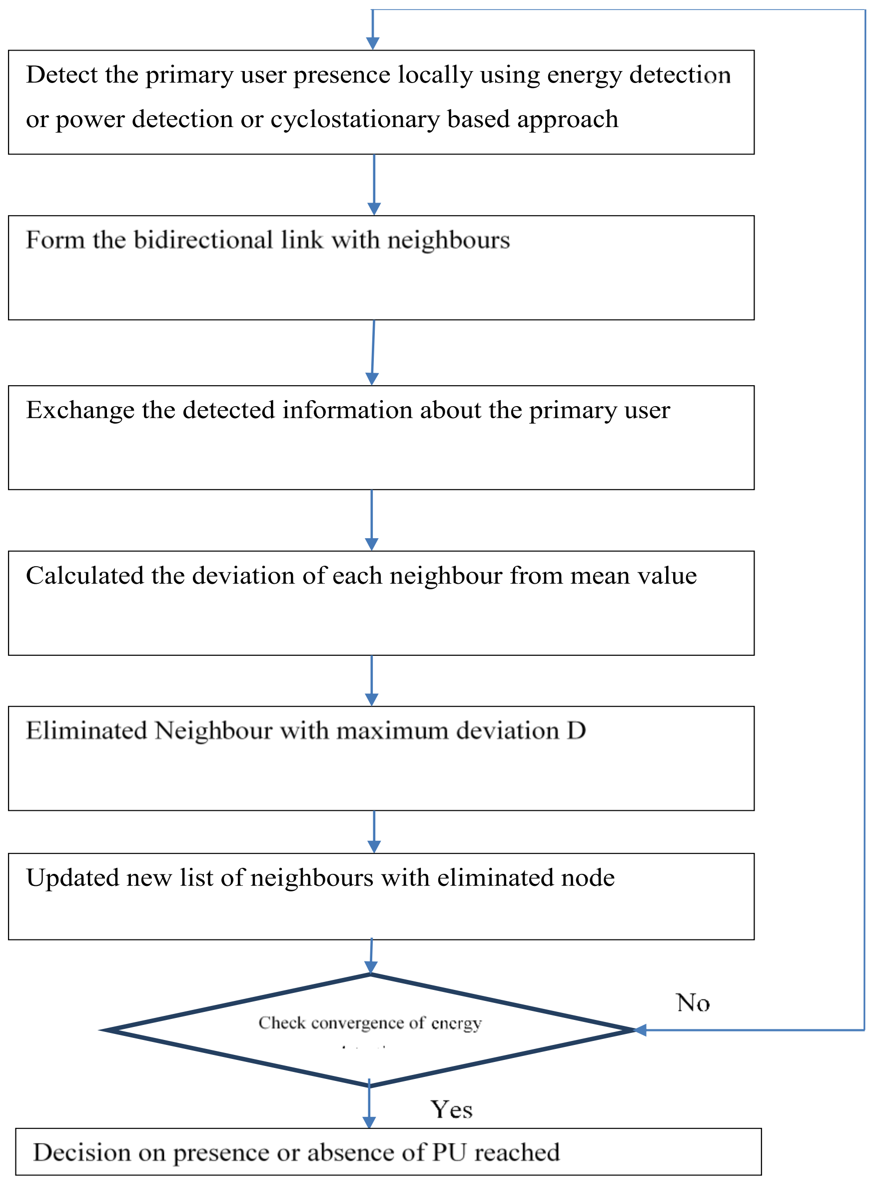


Figure 4-7 Algorithm in CRMANET Using Gradient Descent to Converge on Energy Detection of PU

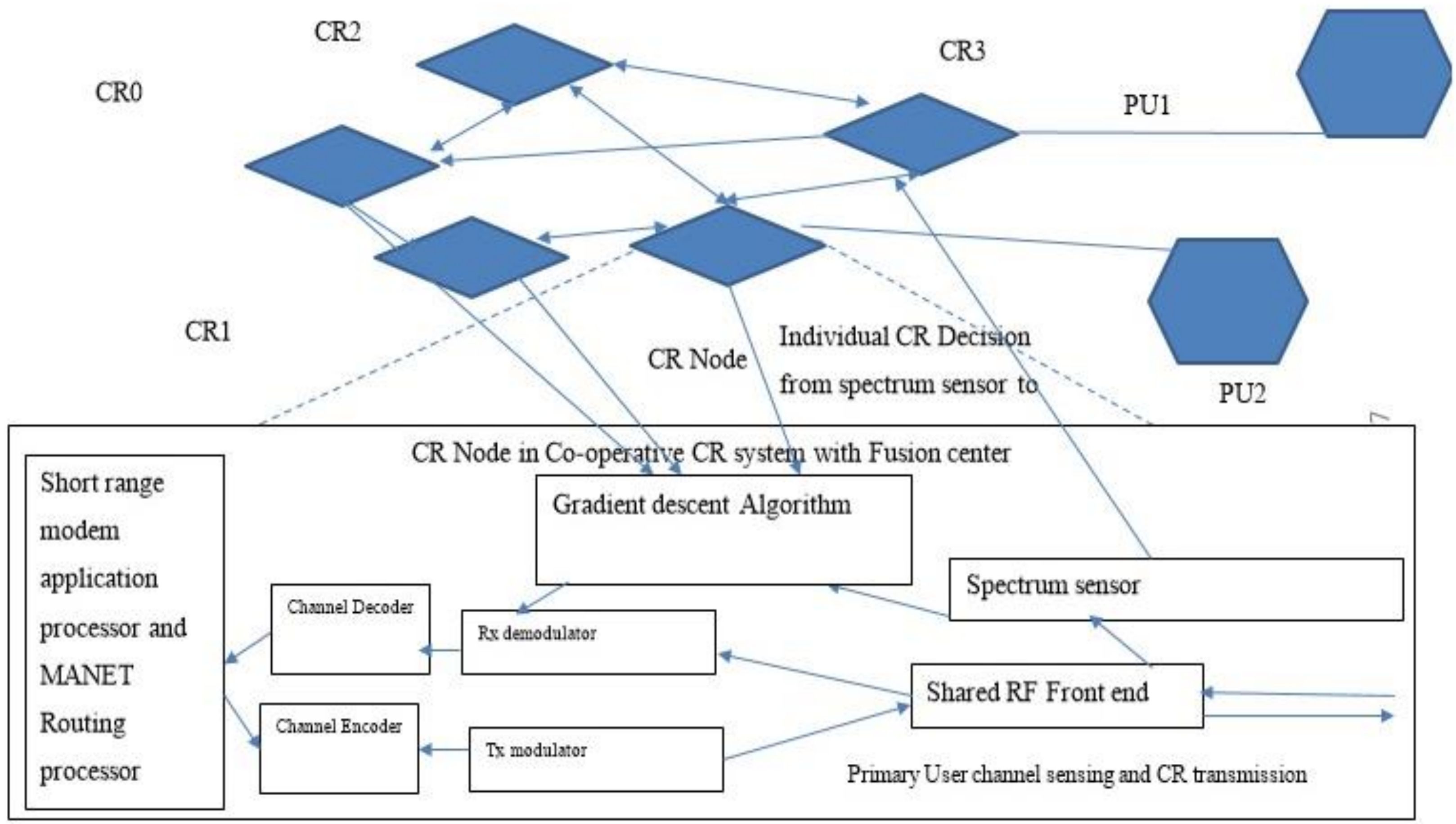


Figure 4.4-8 Co-operative Spectrum Sensing in MANET

Figure 4.8 shows the device architecture of CRMANET node. It comprises of Rx channel chain and Tx channel chain. Each of these chains is comprised of standard communication blocks like channel decoder, demodulator channel encoder, modulator and RF frontend. Apart from these standard blocks, each CRMANET node implements the gradient descent algorithm either as separate block or part of application processor program. Energy or cyclo-stationary based spectrum sensor is implemented to share sensing information with other nodes as well providing sensing information to gradient descent algorithm. Further the communication payload and sensing information is multiplexed into time slots and sent over shared channel. Sensing rate is a trade-off between total energy available for CRMANET node to communicate and sense PU vs reducing the misdetection error.

4.4 Summary

This chapter has discussed the simple co-operative spectrum sensing in heterogeneous networks and MANET. Co-operative spectrum sensing overcomes many of the drawbacks of single sensor spectrum sensing discussed in the chapter 3. But co-operative spectrum sensing as applied to heterogeneous networks has an issue of convergence or sensing time. The convergence time for detecting PU at the fusion centre is longer due to underlying analysis of decision making. Also the overall resource involved in the detection of PU is larger and resource utilization efficiency is lower. CRMANET suffers from similar drawbacks. But in this case, it is more severe because of the Adhoc nature of the network. Frequent disconnections by peer causes the CRMANET to be more unreliable than without CR. CRMANET also will have stronger interference with PU network due to lack of infrastructure support. The significant shortcomings arising out of co-operative spectral sensing are:

1. Requirement of substantial number of CR nodes for sensing single channel
2. There are no methods in the current literature to allocate different channels for sensing so that it is resource optimal

3. In MANET there are problems with convergence rate of the co-operative sensing using gradient descent method because of the associated local minima nature of the solution
4. There is no substantial improvement in usable bandwidth while applying Co-operative spectrum sensing to satisfy Neyman-Pearson Criteria and hence cannot increase the spectrum efficiency by more than 10%
5. In MANET one can apply better methods like SGD to avoid the problem of local minima, but still the goal of enhanced spectral efficiency by increasing the available or usable bandwidth is not fully met

The analysis and formulation of controlled co-operative spectral sensing using binary regression on wireless path-loss curves presented in the next chapter is aimed to mitigate some of the above referred drawbacks of co-operative spectral sensing

Chapter 5 - Co-Operative Spectrum Sensing Using CR Node Binary Decision Regression on Estimated Wireless Path-Loss Curves

This chapter presents a new concept of controlled co-operative spectrum sensing using binary regression on wireless path-loss curves. Using controlled co-operative sensing, the distance of the PU from the fusion centre can be accurately estimated, with an assumption that the PU is operating conforming to the defined mobile terminal specifications. With estimated distance using techniques defined in this chapter and algorithm for allocation of resources, the SNR of the sensing channel is improved over conventional co-operative spectrum sensing. An expression for the determination of the optimal value of CR nodes 'N' required for co –operative spectrum sensing to meet the specified threshold of statistical significance is also presented in this chapter. An algorithm for allocating frequency for sensing and frequency for communication based on CSI, distance and frequency bands is also discussed in this chapter. This chapter also proposes an algorithm to assign nodes for multiband frequency sensing based on CSI and distance from fusion centre. Aiming at the minimisation of interference to PU, this chapter presents a discussion on the operating region and power control of CR nodes using controlled co-operative spectrum sensing. There is also a discussion on the relative improvement in the spectral efficiency of CR enabled network with the incorporation of the proposed controlled co-operative spectral sensing using CR Node Binary Decision Regression on Estimated Wireless path-loss Curves. This chapter also highlights the research opportunities for possible further improvements in controlled co-operative spectrum sensing

5.1 Introduction

Major drawback co-operative spectrum sensing is that, there is no algorithm which can realistically determine to allocate spectrum sensing resources. In the research studies on spectrum sensing in MANET and heterogeneous networks reported in (Yucek T, 2009 and Ranganathan P, 2006), there is no assumption on channel structure. To increase utilisation of usable spectrum thereby to achieve higher spectral efficiency, the spectrum sensing resources must be allocated efficiently. One of the novel contributions of this research is the scheme to allocate frequency of sensing and frequency of communication based on the estimated distance of the PU. Path loss model based distance estimation is considered first and then more intelligent pattern recognition based spectrum detection techniques are considered later. Estimating the presence of PU based on regression of path loss curve provides basic tool to assign resource for sensing the presence of PU and for the communication between different CR nodes.

5.2 Controlled Co-operative Spectrum Sensing Using Binary Regression on Wireless Path-Loss Curves

A simplest form of determining distance of a radio source is to fit the power received into a path loss model, if the transmit power of the standard radio sources is predefined. In CRMANET especially adapting transmit power optimally is very important to avoid interference to heterogeneous networks. Figure 5.1 shows a system model for controlled co-operative spectrum sensing, where the fusion centre (in case of 3G/4G networks, it can be eNodeB) allocates the frequencies for both sensing and communication.

Major difference between system models depicted in Figure 4.1 of chapter 4 and Figure 5.1 of this chapter is the control signals from fusion centre which determines the resource allocation, shown in bidirectional arrow in a dash line between fusion centre and the spectrum sensor in the CR node.

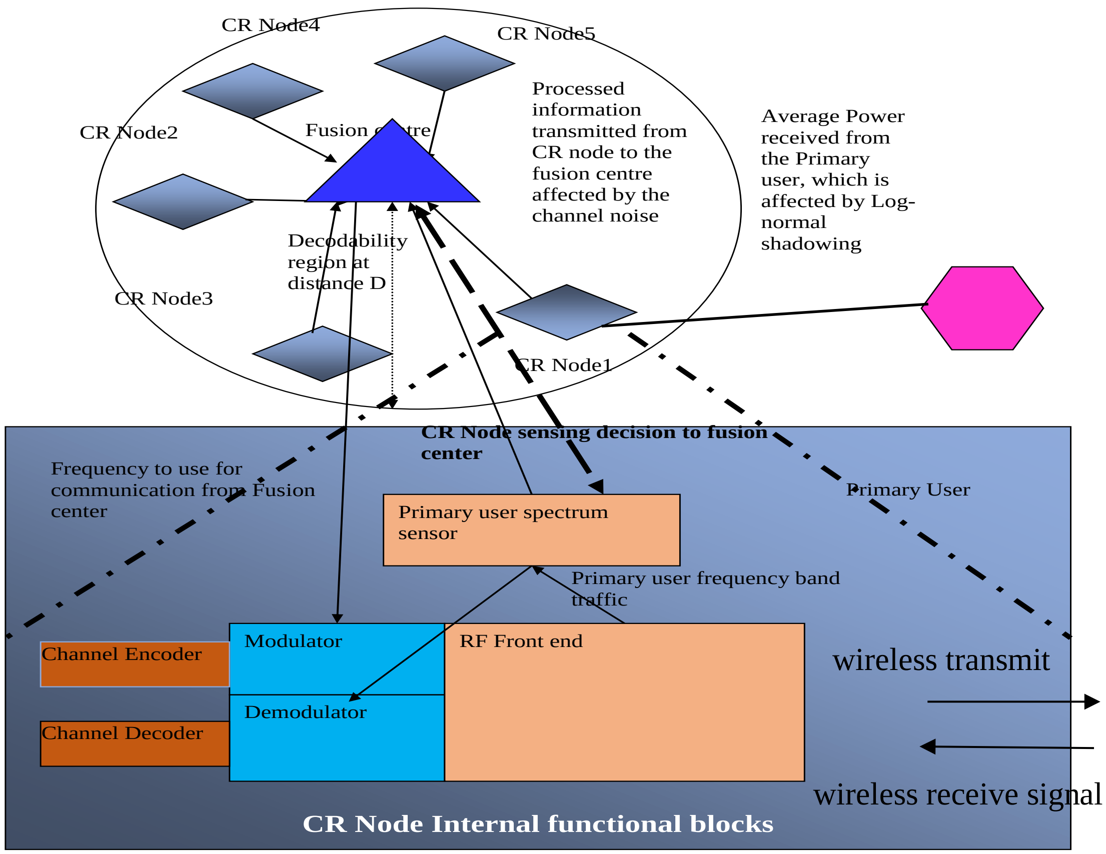


Figure 5-1 Controlled Co-operative Spectrum Sensing with Fusion Centre Allocating Sensing Frequency and Frequency of Communication

5.2.1 System model for Controlled Co-operative Spectrum Sensing Using Binary Regression Wireless Path-Loss Curves

System model for controlled co-operative spectrum sensing heavily depends on the characteristics of radio waves which will effectively determine the attenuation or path loss during its travel from source to destination. System model depends on the distributed detection to estimate the direction of PU and its distance from fusion centre. Unlike current techniques that provide the co-operative spectrum sensing as generic distribution detection (stated earlier in Chapter 2), this research exploits radio propagation to increase probability of detection and decrease probability of false alarm as well as probability of missed detection.

The distribution of CR nodes, primary user and the fusion centre along a straight line is shown in Figures 5.2 and 5.3. Figure 5.2 shows that PU is away from the fusion centre. CR nodes farther from the fusion centre detects the absence of PU since their received power will be below sensitivity of the receiver to detect the transmit power of PU. On the contrary, the CR nodes nearer to the fusion centre report the presence of the PU Therefore consideration of these detections into a detection vs distance profile is shown in Figure 5.2 to obtain the approximate distance of PU from fusion centre.

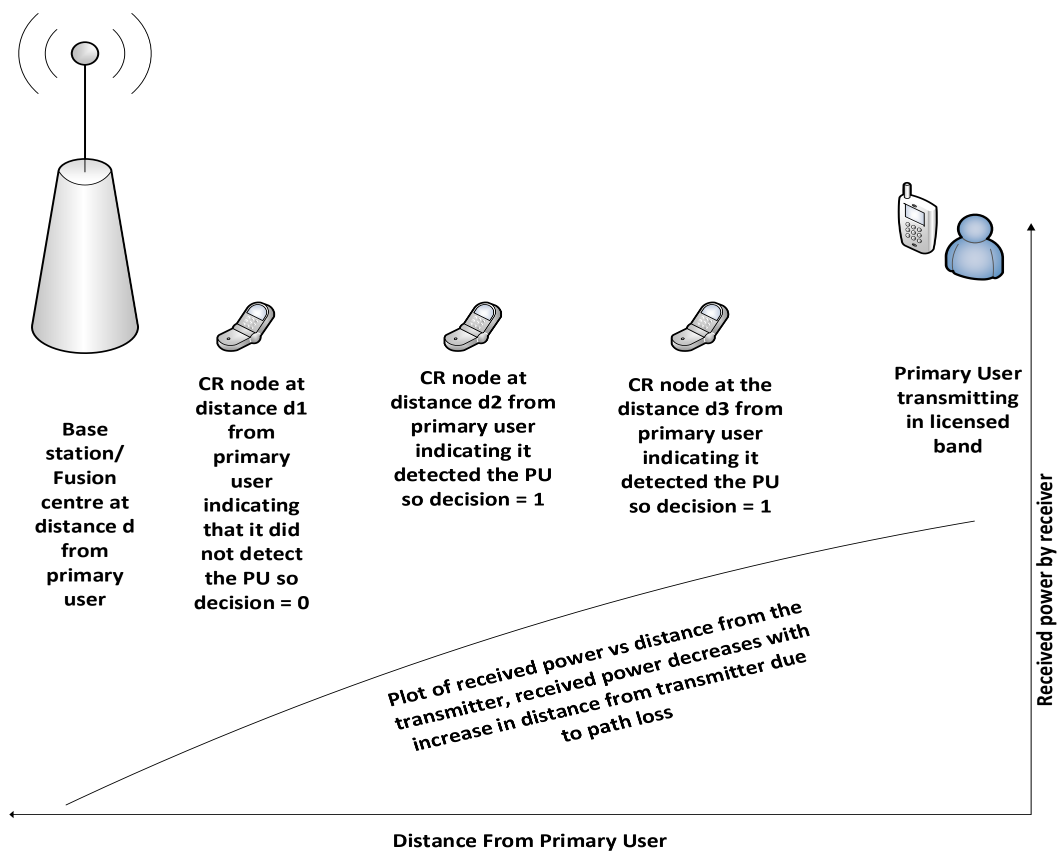


Figure 5-2 Typical Node Distribution and Co-operative Detection with Fusion Centre Away from Primary User

Figure 5.3 shows the case where PU is nearer to fusion centre and detection by CR nodes which are away from fusion centre. In this case the CR nodes which are nearer to fusion centre detects the PU. CR nodes which are away from fusion centre does not detect the presence of PU. This is because due to the path loss, received power for CR nodes which are farther away from PU will be below the receiver sensitivity of CR nodes and then report the fusion centre the absence of PU. Thus, in both cases one can capture the approximate curve for the PU transmit signal path loss and hence estimate the approximate distance of PU from the fusion centre.

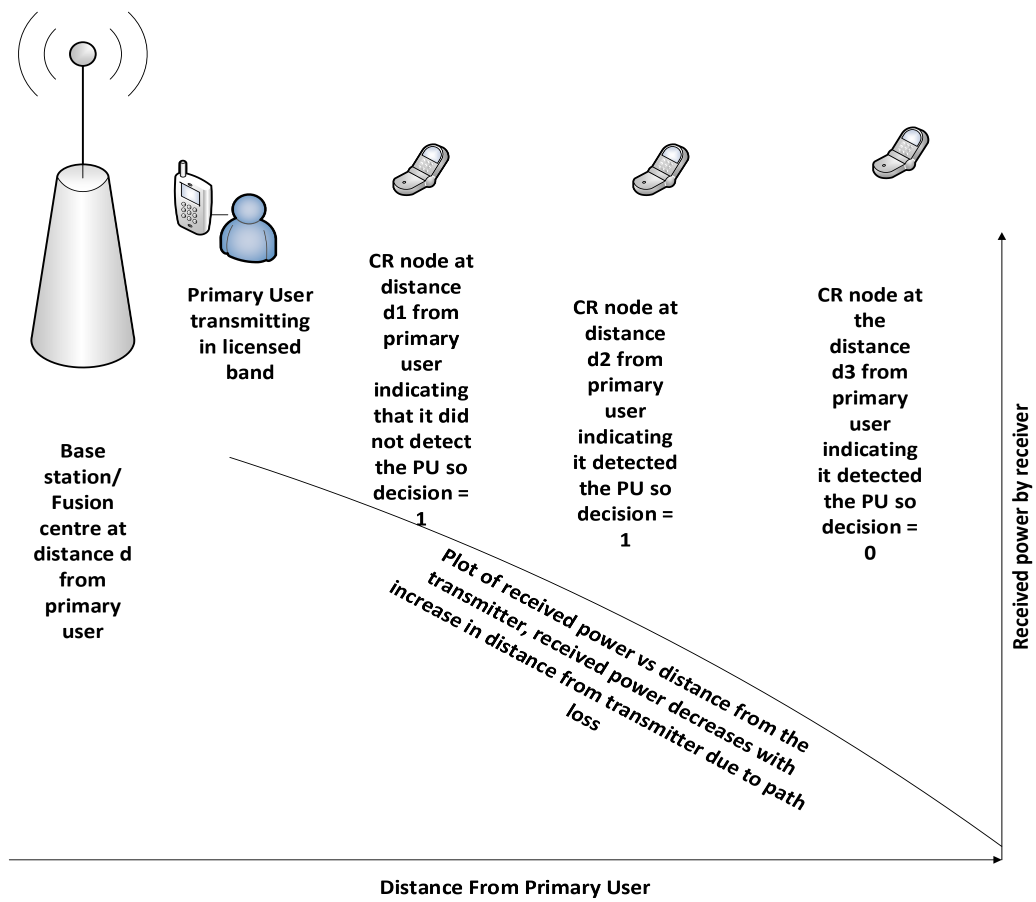


Figure 5-3 Typical Node Distribution and Co-operative Detection with Fusion Centre Nearer to Primary User

Propagation models are traditionally used to predict the signal strength at a given distance from the source. Log-distance Path Loss model and Log-Normal Shadowing are discussed in (Theodore S. Rappaport, 1996).

In (Theodore S. Rappaport, 1996), the mean or expected propagation loss in dBm is represented by the smooth curve. This curve represents the large-scale propagation loss. The volatile curve that oscillates around the large-scale propagation loss curve is the curve of small-scale fading. One can note that actual measured signal power can be accurately represented by small scale fading at any space and time co-ordinates within the coverage area of transmitter. It should also be noted that apart from the time and space, the frequency dictates the large-scale path loss curve.

In the derivation of the mathematical formulation for the probability of detection, there is an assumption of single frequency of operation initially. Log-Distance Path loss model is assumed for large scale path loss model and Raleigh fading is assumed for small scale fading.

Log-distance Path Loss Model is given by the equation:

$$\mathrm{PL(dB)} = \mathrm{PL(d0)} + 10\mathrm{nlog}(\mathrm{d}/\mathrm{d0}) \tag{5.1}$$

Where,

n : Path loss exponent

PL(dB): Expected receiver power at distance d

PL(d): Receiver power measure at a reference distance d0

For the simulations, urban area cellular radio environment is considered. For this scenario, the path loss exponent ranges from 2.7 to 3.5. n=3 is assumed for the MATLAB simulations.

Received Power at the CR node which is due to power transmitted from PU can be modeled as

$$\mathrm{Rxp(dBm)} = \mathrm{Txp(dBm)} - \mathrm{PL(dBm)} \tag{5.2}$$

Where,

Rxp is received power at the CR receiver

Txp is transmitted power of the PU

If the transmitted power from the transmitter is known and which can be constant and minimum received power below which CR cannot detect the PU is given by Rxp(min) = λ where λ is the sensitivity of the receiver. Therefore, with λ and Txp known and are they are also constant, only variable in Equation (5.2) is PL(dBm). Path loss predicted by equation (5.1) varies largely between the same Transmitter-Receiver separation, rather than the mean value predicted by the Equation (5.1). Past measurements have shown that Path loss at any distance d, at a location is a random and distributed log-normally about the value given in Equation (1). From (Theodore S. Rappaport,1996)

$$\mathrm{PL(d)[dB]} = \overline{PL(d)}(\mathrm{do}) + 10\mathrm{nlog}\left(\frac{d}{d0}\right) + \mathrm{X}\sigma \tag{5.3}$$

Considering the received power at distance'd' is given by Pr(d), the transmit power is given by Pt[dBm] and path loss at distance d is given by PL(d)[dB]. Then the received power at distance is given by

$$Pr(d)[dBm] = Pt[dBm] - PL(d)[dB] \tag{5.4}$$

Where X_σ is a zero mean Gaussian distributed random variable (in dB) with standard deviation σ (in dB). The phenomenon called *log-normal shadowing*, is for obtaining different path losses for the same Transmitter-Receiver separation. This is because of various levels of clutter on the propagation path. Shadowing is the phenomenon in which the measured signal levels at a point in space for a given Transmitter-Receiver separation have a Gaussian (normal) distribution about the mean from ideal Equation (5.2).

Since PL(d) is a Gaussian random variable, so will be Pr(d). Probability of the received signal level (in dBm) exceeding a certain value γ can be calculated from cumulative density function as

$$P_{rcv}[P_r(\mathrm{d}) > \gamma] = \mathrm{Q}\left(\frac{\gamma - P_r(d)}{\sigma}\right) \tag{5.5}$$

Similarly, the probability of the received signal power level being below γ is given by

$$P_{rcv}[P_r(\mathrm{d}) < \gamma] = \mathrm{Q}\left(\frac{P_r(d) - \gamma}{\sigma}\right) \tag{5.6}$$

Where

P_{rcv} () is the probability of received power below threshold γ

γ is the receiver sensitivity threshold

Pr(d) is the power received at distance d

σ is the standard deviation

Q () is Q function

Equations (5.5) and (5.6) can be directly used for detection and false alarm probabilities in distributed detection. Typical CR devices produce maximum output power in the range of 25 dBm. So for an assumed value of P0 as 25 dBm and d0 as 1m, the receiver sensitivity of 3G/4G devices is the range of -120 dBm. For a sensitivity of receiver = -110 dBm and P0 = 20 dBm, the obtained path loss curve is shown in Figure 5.4.

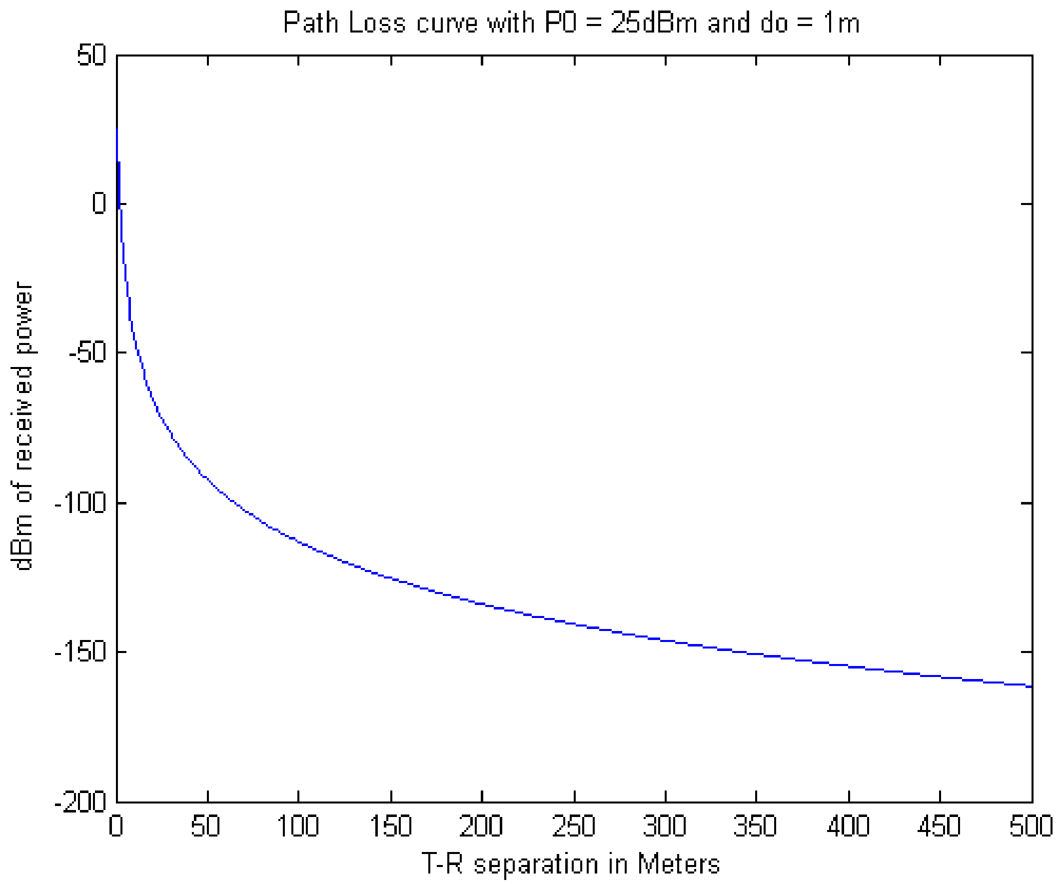


Figure 5-4 Received Signal Power Vs T-R Separation

The original contribution of this research is overcoming the assumption that the probability of detection is only affected by the channel noise. Channel noise has its effects on overall probability of detection at fusion centre. But the detection at the individual nodes is affected by log-normal shadowing when the log-distance model of propagation is considered.

In a system model, one can consider 2 channels namely $Ch_{PU\text{-}CR}$ (PU to CR channel) and $Ch_{CR\text{-}FU}$ (CR to fusion centre channel). Channel $Ch_{PU\text{-}CR}$ (PU to CR channel) is used to detect the transmit power of PU. It is important that CR node receives the signal from PU, whose power is above the sensitivity of the CR node receiver. For this channel, the chief source of power degradation is modelled as log-normal shadowing. Log-distance path loss model is used for modeling the propagation loss and upon that log-normal shadowing is modelled to account for the further degradation of signal power of at PU. It is assumed that the effects of log-normal shadowing will be much higher than the effect of SNR on the signal and hence one can be justified to ignore the effect of SNR **.** For the channel $Ch_{CR-FU,}$ the information passed from CR to PU is more important than just the signal power since fusion centre needs to obtain correct information transmitted by the CR node. If the information transmitted by CR node is distorted by the noise in the channel, then it adds to statistical insignificance of whole measurement at the fusion centre. It can happen that the two channels can operate in a separate frequency band altogether or they can act in same frequency band.

5.2.2 Linear Regression and Decision Making at the Fusion Centre

Detection of presence of PU at fusion centre can be carried out as follows. Decisions arrived by individual CR nodes are collected and regressed on expected decision with estimated distance**.** Fusion centre receives the decisions from various CR nodes and then combines them with a simple fusion function to arrive at fused decision. Fusion function can be simple OR or AND function or more complex functions with weighted decisions from each CR nodes. Linear curve fitting can be used. This is because detection reduces the probability at decodability boundary at distance d, where it is expected that the received power will be $S+/-V_f$**,** where S is the receiver sensitivity and V_f is the noise.

Fusion centre receives the processed information in terms of decisions from each CR node. Each CR node sends out its processed information to the fusion centre. Fusion centre executes the regression on the normalized information received from the CR nodes. Depending on the *Statistical significance* of the regression, fusion centre computes the presence and absence of the PU as well as the distance of the PU from the fusion centre.

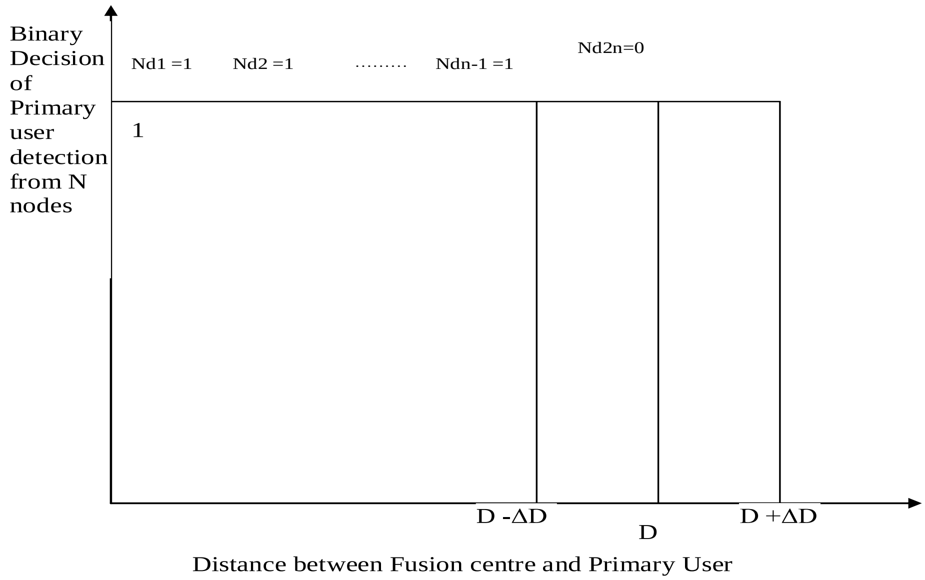


Figure 5.5-5 Expected and Actual Fusion at the Centre with Error Distance D

Figure 5.5 shows the shift in decodability distance D due to error in detection by an incremental distance ΔD. Decisions within decodability area would be more reliable when d << D because of stronger signals at receiver.

Ideal equation for fusing decision at the Fusion centre is given by

$$E[Ni] = \begin{cases} 1 & d \le D \\ 0 & d > D \end{cases} \qquad (5.7)$$

Where E () is expected detection decision by Node N_i,

d is the distance of node from PU

D is the range of decodability area

Actual decisions received from the CR nodes can be written as N_i: Actual combined decision from all nodes at the fusion centre is:

$$N_{iActual} = \begin{cases} 1 & d \le D \pm \Delta D \\ 0 & d > D \pm \Delta D \end{cases} \tag{5.8}$$

The error $\pm \Delta D$ is a function of log normal shadowing.

Curve fitting error can be modeled in terms of the difference in distance ΔD. Assuming tolerable error threshold to confirm the presence of PU is τ, then detection threshold in terms of distance at which a CR node provides zero decision is given by

$$P_{detect} = \begin{cases} 1 & dt < \Delta D - \tau \\ 0 & dt > \Delta D + \tau \end{cases} \tag{5.9}$$

Where P_{detect} is the detect decision from the fusion centre and dt is the distance from the zero decision CR node to fusion centre. Figure 5.6 shows the decision by CR nodes at different locations from fusion centre. Difference between Figure 5.5 and Figure 5.6 is that CR nodes are spread either side of the fusion centre in case of Figure 5.6. In Figure 5.5, it is assumed that fusion centre to be at origin of reference axes.

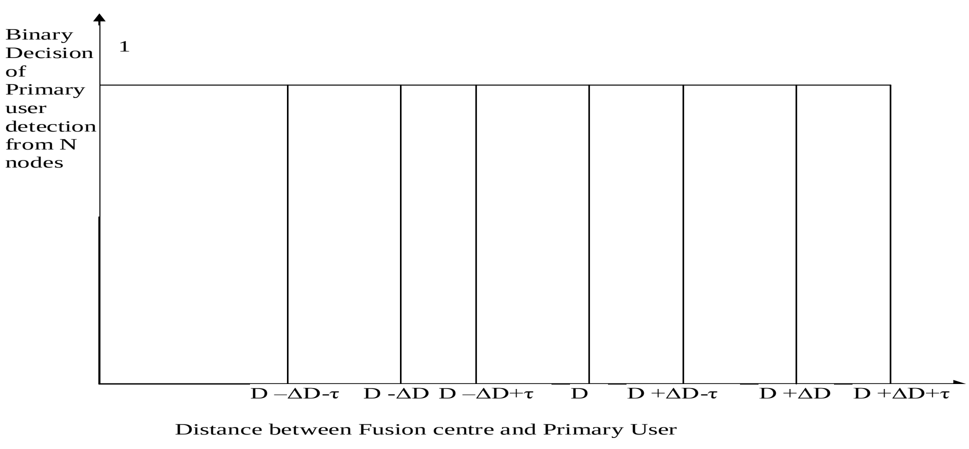


Figure 5.5-6 Decision Boundary with Decision Threshold τ at Fusion Centre

5.2.3 Statistically Significant Regression and Number of Nodes Required in Co-Operative Spectrum Sensing

To perform the linear regression on the information received from the individual nodes, fusion centre has to determine the number of sample points required to make the regression statistically significant. This means that the fusion centre needs to determine number of nodes required for co-operative spectrum sensing. So far it is assumed the statistical nature of path-loss model is affected by the flat fading and its effect on probability of detection. Apart from it, it is necessary to consider the channel noise that will affect the transfer of the decision made by the CR node to the fusion centre.

The outcome of regression, R^2 of the regression should be greater than threshold T to consider it not only as statistically significant but also from the reliable aspect perspective of the decision of the fusion centre. R^2 value of the regression depends on the channel noise between CR node and fusion centre.

The number of nodes required for co-operative spectrum sensing is dependent on the threshold T for a given channel noise model. Figure 5.7 and Figure 5.8 show the difference between actual decision sampled and ideal decision in case of single and multiple CR nodes respectively. The decisions are plotted with respect to the distance from fusion centre. As shown in the results of Figure 5.8, it is observed that under ideal conditions, decision across the CR nodes placed in straight line from the fusion centre changes from ‘1’ to ‘0’ around distance D, which is the boundary of decodability region. But due to the channel noise, the decision from various CR nodes can be subjected to missed detection and as described in Figure 5.8, many decisions can be ‘0’ even when CR nodes are nearer to PU.

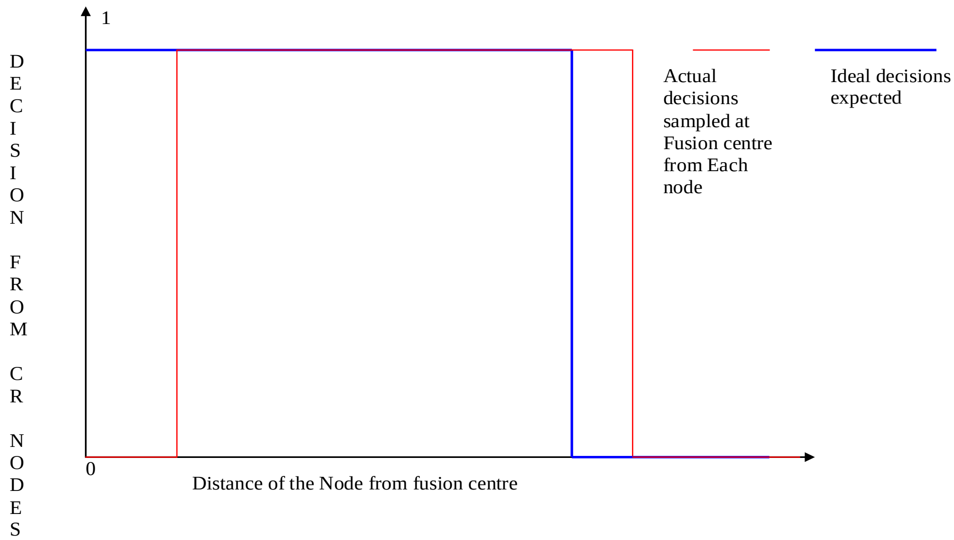


Figure 5.5-7. Example of Statistically Significant Decisions from CR Node in Co-operative Spectrum Which are Sampled at Fusion Centre

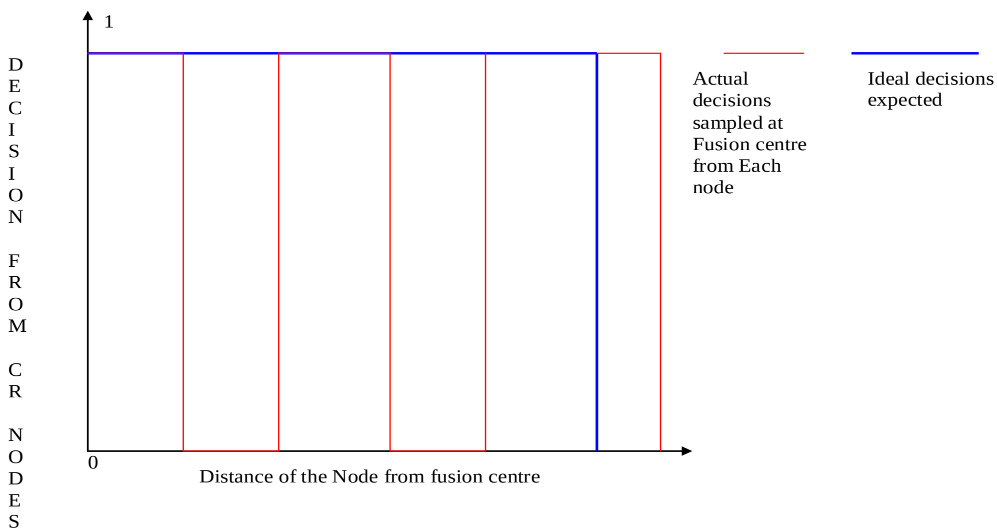


Figure 5.5-8 Example of Statistically Insignificant Decisions from CR Node in Co-operative Spectrum which are Sampled at Fusion Centre

5.2.4 Calculation of the Statistical Significance from the Linear Regression

As described in section 5.2.3, the ideal decision making by CR nodes in the co-operative spectrum sensing is not possible because of noisy wireless channel. So statistical methods are invoked to obtain the most likelihood estimate of the decisions made by CR nodes. Regression is performed on the equation:

$$y = \begin{cases} 1, d < D \\ 0, d > D \end{cases} \tag{5.10}$$

Equation (5.10) is a linear equation. Linear regression is performed on this as follows: Sample Coefficient of determination is defined as

$$r^2 = 1 - \frac{\sum (Y - \hat{Y})^2}{\sum (Y - \bar{Y})^2} \tag{5.11}$$

Where

r^2 : Sample coefficient of determination

Y : Expected value of the decisions

$\hat{Y}$: Observed Value of the decisions

$\bar{Y}$: Mean value of observed decisions

Sample Coefficient of Correlation is given by:

r = $\sqrt{r^2}$

Sign of r is always considered positive because slope of the line is always positive. Value of r^2 closer to 1 indicates very high SNR at the fusion centre and perfect regression to the expected values of the decision. Values closer to 0 indicate the noisy channel and hence the sampled decisions from CR nodes are not statistically significant. One can assume the statistical significance of the sampled decision depending on the ω, the statistical significance threshold.

Thus, it is possible to have a representation in the form of

$$\left. \begin{array}{l} r^2 > \omega \\ r^2 < \omega \end{array} \right) \begin{array}{l} significant \\ insignificant \end{array} \tag{5.12}$$

Where ω is statistical significance threshold.

5.2.5 Analysis of Co-operative Spectrum Sensing based on Path Loss Model with Linear Regression at Fusion Centre

One of the methods to make likelihood decision at fusion centre is perform the statistical significance of the decisions. This is discussed in the previous sub section. Other method for decision process involves co-operative spectrum sensing system around minimizing error probabilities. System model of co-operative spectrum sensing is given by

$$\mathrm{y(n)} = \left(\begin{array}{ll} w(n) & Ho \\ h(n) * x(n) + w(n) & H1 \end{array} \right. \tag{5.13}$$

Where,

w(n) is the Additive White Gaussian Noise (AWGN)

h(n) is the channel impulse response

x(n) is the signal transmitted from the CR node.

y(n) is the signal received at the fusion centre

H0 is the case where the signal from CR node is affected from the noise when received at the Fusion centre

H1 is the case of signal detected at Fusion centre

One can assign the following probability cases for signal reception at the fusion centre using basic detection theory.

Probability of correct detection at fusion centre = Pdf = P(x|x)

Probability of false Alarm at the fusion centre = Pff = P(x|x')

Conditional probabilities are directly affected from the channel noise. For AWGN channel model and assuming basic BPSK signaling, Bit error probability is given by:

$$P_B = Q\left(\sqrt{2Eb/N}\right) \tag{5.14}$$

Where Eb/N is the Signal to Noise ratio at the fusion centre.

By substituting Eb/N = λ, Equation (5.14) can be written as

$$P_B = Q(\sqrt{2\lambda}) \tag{5.15}$$

Where Q function is defined as $Q(x) = 1 - \phi(x)$, where $\phi(x)$ is a cumulative distribution of normal random variable.

Total probability of detection at fusion centre due to correct detection at the CR node is given by

$$Pdf = (1- P_B)*\text{Probability of detection at CR node} \tag{5.16}$$

Probability of detection at the CR node is given by the Log –normal shadowing. Assuming that receiver sensitivity as γ and expected received signal power according the log-distance path loss model as Pr(d) at the distance d from PU. Probability of correct detection at fusion centre is given by

$$P_{df} = (1- P_B)*(1- Q\left(\frac{\Pr(d)-\gamma}{\sigma}\right)) \tag{5.17}$$

$$P_{df} = (1 - Q(\sqrt{2\lambda})) * (1 - Q\left(\frac{\Pr(d)-\gamma}{\sigma}\right)) \tag{5.18}$$

Probability of False Alarm at fusion centre is given by, P_{ff}

$$P_{ff} = PB * Q\left(\frac{\gamma-\Pr(d)}{\sigma}\right)$$

$$P_{ff} = Q(\sqrt{2\lambda}) * Q\left(\frac{\gamma-\Pr(d)}{\sigma}\right) \tag{5.19}$$

Probability of missed detection at fusion centre is given by P_{mf}

$$P_{mf} = Q(\sqrt{2\lambda})*(1- Q\left(\frac{\Pr(d)-\gamma}{\sigma}\right)) \tag{5.20}$$

Where

γ is sensitivity of the receiver in dBm

λ is SNR of the channel

Q( ) : Q function or Gaussian Error function.

P_r(d) is expected pathloss at the distance d from the reference distance d0 as per log distance path loss model

σ : is the standard deviation of the Gaussian error function defined in Equations (5.5) and (5.6)

5.2.6 Interpretation of Probability of Detection and Probability of False Alarm at the CR Node

From the Equations (5.16) and (5.17) defined in the previous sub section, it is seen that probability of detection increases with difference in ($P_{r(}d)$-γ). Based on this, the following inferences can be drawn. If the CR node is nearer to the PU, probability of detection is higher. Also the false alarm rate is lower if the distance between the PU and CR is smaller. Probability of detection also depends on the sensitivity of the receiver. If the sensitivity of receiver is lower, probability of detection increases. However due to limitations of physics, receiver detection cannot be at lower threshold beyond certain limits. Therefore, it is reasonable for one can consider decodability area is directly proportional to the distance of the PU and transmit power of the PU. Functioning of the co-operative spectrum sensing is limited by the probability of missing a detection (P_{mf}). As indicated by (Yucek T, 2009), P_{mf} is directly limited by the reporting channel bit error ($Ch_{CR\text{-}FU}$).

5.2.7 Cumulative Probabilities at the Fusion Centre

Path loss model regression/Correlation decreases the miss detection probability and false alarm probability. It increases the probability of detection. Cumulative probability of detection is described as probability of K out of N detections is false in the N node CR network, such that regression is no more statistically significant. One can assume K-n miss detection and n false alarm.

Probability of missed detection at fusion centre is given by

$$P_{Fu}(m)= P(r^2 < \omega|\ p_{mi}\ (i=1\ldots.N)) \qquad (5.21)$$

Where r is statistical significance, ω is the decision threshold, p_{mi} is missed detection probability of individual CR node and N is number of CR nodes

Cumulative probability of missed detection such that at least missed detection is given by

$$P_{Fu}(m) = \sum_{i=0}^{N-K} \prod_{i}^{K+i} pi \prod_{j=K=i+1}^{N-1} (1 - pj) \qquad (5.22)$$

Where

p_i is the probability of the correct detection

p_j is probability of no detection

$P_{Fu}(m)$ is a cumulative missed detection at fusion centre for K or N nodes missing the detection of PU

The cumulative probability at fusion centre taking mean probability can be simplified by considering it as expected probability of missed detection at each node. This can be achieved by noting the observation that missed detection will be dependent on the reporting channel SNR. Mean value of missed detection probability with respect to distance is given by:

$$p_{mif} = \sum_{N} \frac{pmi}{N} \qquad (5.23)$$

Where

p_{mi} is missed probability of individual node

p_{mif} is missed probability at fusion centre

N is number of CR nodes

Probability of missed detection at the Fusion centre is given by:

$$P_{Fu}(m) = \binom{N}{K} pmif^{K} (1\text{- pmif})^{N\text{-}K} \tag{5.24}$$

Similarly, probability of false alarm at fusion centre is given by:

$$P_{Fu}(f) = P(r^2 < \omega |\, p_{fi}\ (i=1\ldots.N)) \tag{5.25}$$

Where p_{fi} is probability of false alarm for individual nodes

Mean Value of missed detection with respect to distance is given by p_{fif}

$$p_{fif} = \sum_{N} \frac{pfi}{N} \tag{5.26}$$

Probability of false alarm at the Fusion centre is given by $P_{Fu}(f)$

$$P_{Fu}(f) = \binom{N}{K} pfif^{K} (1\text{- pfif})^{N\text{-}K} \tag{5.27}$$

$$P_{Fu}(f) = \binom{N}{K} pmif^{K} (1\text{- pmif})^{N\text{-}K} + \binom{N}{K} pfif^{K} (1\text{- pfif})^{N\text{-}K} \tag{5.28}$$

Where N is total number of CR nodes in co-operative spectrum sensing

K is sum of number of nodes missing detection or providing false alarm

For number of CR nodes less than K, regression will no more be statistically significant. The formulation for cumulative probability distribution of this thesis is more complete and accurate than the one presented in (Yucek T, 2009) for general case, where the probabilities are considered in isolation. Because of the regression/correlation on the path loss model, the probability of detection improves over the formulation suggested in (Yucek T, 2009). The analysis of (Yucek T, 2009) does not consider of the path loss information into the final decision of detection.

5.2.8 Optimal Number of Nodes in the Co-Operative Spectrum Sensing

Number of nodes required for the CR co-operation is directly proportional to Transmit power and distance of PU from fusion centre. It also depends on the statistically significant threshold of the correlator used at the fusion centre. It is possible to consider sensing time as directly proportional to number of nodes in the co-operation with fusion centre. Statistical significance of the regression/correlation is asymptotically dependent on the number of samples in the regression. Therefore, with the assumption that regression/correlation is independent of the number of samples or one has enough samples for acceptable SNR to get statistically significant result, number of CR nodes required is only dependent on the quality of channel between fusion centre and the CR nodes. Optimal number of nodes can be obtained by partial differentiation of total probability at fusion centre with respect to N.

$$\partial \frac{PFu(T)}{\partial N} = 0 \tag{5.29}$$

$$\partial \frac{}{\partial N} \left(\begin{matrix} N \\ K \end{matrix} \right) pmif^{K} (1\text{- pmif})^{\text{N-K}} + \partial \frac{}{\partial N} \left(\begin{matrix} N \\ K \end{matrix} \right) pfif^{K} (1\text{- pfif})^{\text{N-K}} = 0 \tag{5.30}$$

It is known that,

$$\partial \frac{}{\partial n} \binom{n}{k} = \binom{n}{k} \sum_{i=0}^{k-1} \frac{1}{n-i} \tag{5.31}$$

$$\binom{N}{K}\sum_{i=0}^{k}\frac{1}{N-i}\ pmif^{K}(1\text{-}\ \mathrm{pmif})^{\text{N-K}}+\binom{N}{K}pmif^{K}(1\text{-}\ \mathrm{pmif})^{\text{N-K}}\ln(1\text{-}\ \mathrm{pmif})+\binom{N}{K}\sum_{i=0}^{l}\frac{1}{N-i}$$

$$pfif^{K}(1\text{-}\ \mathrm{pfif})^{\text{N-K}}+\binom{N}{K}pfif^{K}(1\text{-}\ \mathrm{pfif})^{\text{N-K}}\ln(1\text{-}\ \mathrm{pfif}))=0 \qquad (5.32)$$

$$\sum_{i=0}^{k}\frac{1}{N-i}\ pmif^{K}(1\text{-}\ \mathrm{pmif})^{\text{N-K}}+pmif^{K}(1\text{-}\ \mathrm{pmif})^{\text{N-K}}\ln(1\text{-}\ \mathrm{pmif})+\sum_{i=0}^{l}\frac{1}{N-i}\ pfif^{K}(1\text{-}$$

$$\mathrm{pfif})^{\text{N-K}}+pfif^{K}(1\text{-}\ \mathrm{pfif})^{\text{N-K}}\ln(1\text{-}\ \mathrm{pfif}))=0 \qquad (5.33)$$

$$\sum_{i=0}^{k}\frac{1}{N-i}\ (pmif^{K}(1\text{-}\ \mathrm{pmif})^{\text{N-K}}+pfif^{K}(1\text{-}\ \mathrm{pfif})^{\text{N-K}})+pmif^{K}(1\text{-}\ \mathrm{pmif})^{\text{N-K}}\ln(1\text{-}\ \mathrm{pmif})+$$

$$pfif^{K}(1\text{-}\ \mathrm{pfif})^{\text{N-K}}\ln(1\text{-}\ \mathrm{pfif}))=0 \qquad (5.34)$$

This solution assumes that for K << N, one can approximate $\sum_{i=0}^{k}\frac{1}{N-i}$ = K/N. As a result, Equation (5.34) can be written as:

$$\text{K/N}(pmif^{K}(1\text{-}\ \mathrm{pmif})^{\text{N-K}}+pfif^{K}(1\text{-}\ \mathrm{pfif})^{\text{N-K}})=-(pmif^{K}(1\text{-}\ \mathrm{pmif})^{\text{N-K}}\ln(1\text{-}\ \mathrm{pmif})+pfif^{K}$$

$$(1\text{-}\ \mathrm{pfif})^{\text{N-K}}\ln(1\text{-}\ \mathrm{pfif})) \qquad (5.35)$$

Equation (5.35) can be written as:

$$\text{N/K}=((pmif^{K}(1\text{-}\ \mathrm{pmif})^{\text{N-K}}+pfif^{K}(1\text{-}\ \mathrm{pfif})^{\text{N-K}})/-(pmif^{K}(1\text{-}\ \mathrm{pmif})^{\text{N-K}}\ln(1\text{-}\ \mathrm{pmif})+$$

$$pfif^{K}(1\text{-}\ \mathrm{pfif})^{\text{N-K}}\ln(1\text{-}\ \mathrm{pfif})) \qquad (5.36)$$

$$\text{N} = \frac{\text{K}*((1\text{-}\mathrm{pmif})^{\text{N-K}}+(1\text{-}\mathrm{pfif})^{\text{N-K}})}{-((1\text{-}\mathrm{pmif})^{\text{N-K}}\ln(1\text{-}\mathrm{pmif})+(1\text{-}\mathrm{pfif})^{\text{N-K}}\ln(1\text{-}\mathrm{pfif}))} \qquad (5.37)$$

It should be noted that ln(1-pmif) and ln(1-pfif) are negative numbers. Further it is possible have the substitution invoking the relationship K = (1-ω)*N, where ω is the statistical significance constant. Therefore it is possible to establish the direct relation between statistical significance threshold and the number of nodes required in the co-operation.

$$N = \frac{K*((1-pmif)^{K(\frac{\omega}{1-\omega})} + (1-pfif)^{K(\frac{\omega}{1-\omega})})}{-((1-pmif)^{K(\frac{\omega}{1-\omega})}\ln(1-pmif) + (1-pfif)^{K(\frac{\omega}{1-\omega})}\ln(1-pfif))} \tag{5.38}$$

Equation (5.38) determines the optimal value of CR nodes ‘N’ required for co –operative spectrum sensing. Sensing time τ can be assumed to be directly proportional to N with proportionality constant ξ, which is dependent on processing time at each node and ρ as processing time at fusion centre. Propagation time from all CR nodes to fusion centre and decision to percolate to network elements is assumed to be constant φ.

$$\tau = \xi * N + \rho + \varphi \tag{5.39}$$

Assuming that all other factors are constant, the sensing time is solely dependent on the number of nodes used. Number of nodes used again is largely dependent on the error rate of report channel and statistical significance threshold of regression function at the fusion centre.

5.3 Simulation Results from Controlled Co-operative Spectrum Sensing Using Binary Regression on Wireless Path-Loss Curves

In this section, simulation results on the variation missed probability of detection as a function of distance of PU from fusion centre are presented. Figure 5-9 depicts the probability of miss detection Vs Distance in meters from PU at different SNR of CHFuCR. The range of SNR considered for the simulation results varies from 0.5 dB to 2 dB.

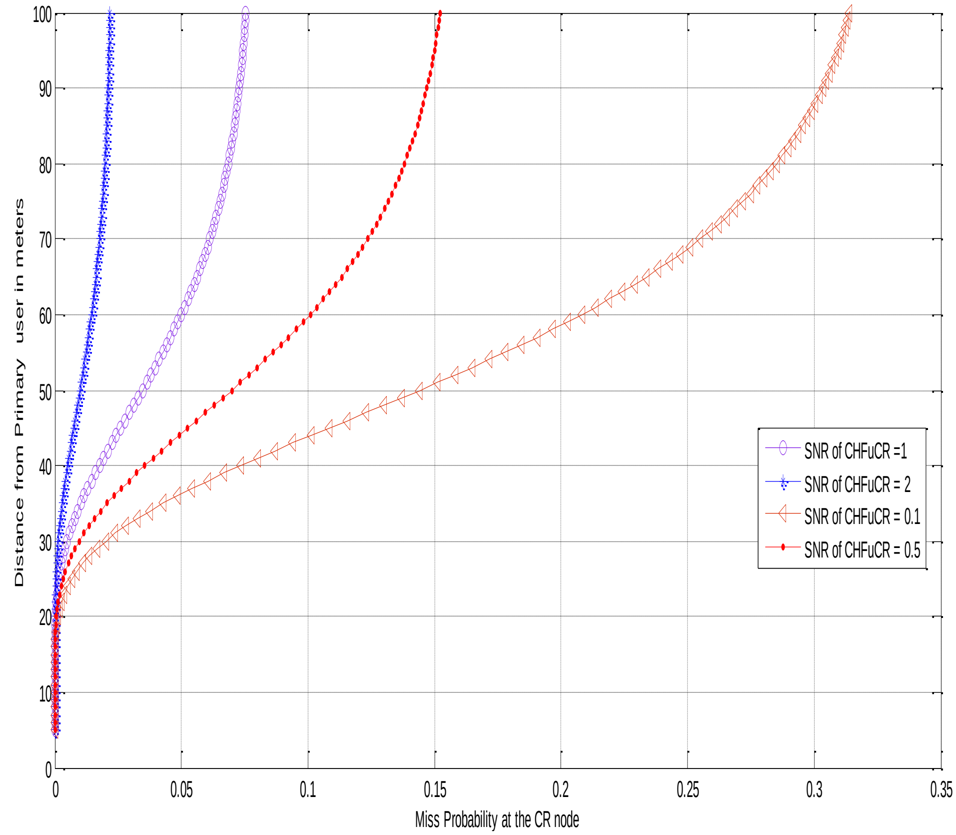


Figure 5.9 Probability of Miss Detection Vs Distance in Meters from Primary User at Different SNR of CHFuCR Using Equation (5.20)

The results of Figure 5.9 reveal that reporting SNR of channel CHFuCR should be minimal for the minimum probability of missed detection for a given decodability area, sensitivity of CR detector and transmit power of PU. Using Equation (5.20), the missed detection is plotted for varying values of SNR. The results confirm that higher SNR leads to higher missed detection. Simulation results depicting the effect of variation in probability of false alarm on probability of missed detection are shown in Figure 5.10 for varying values of SNR.

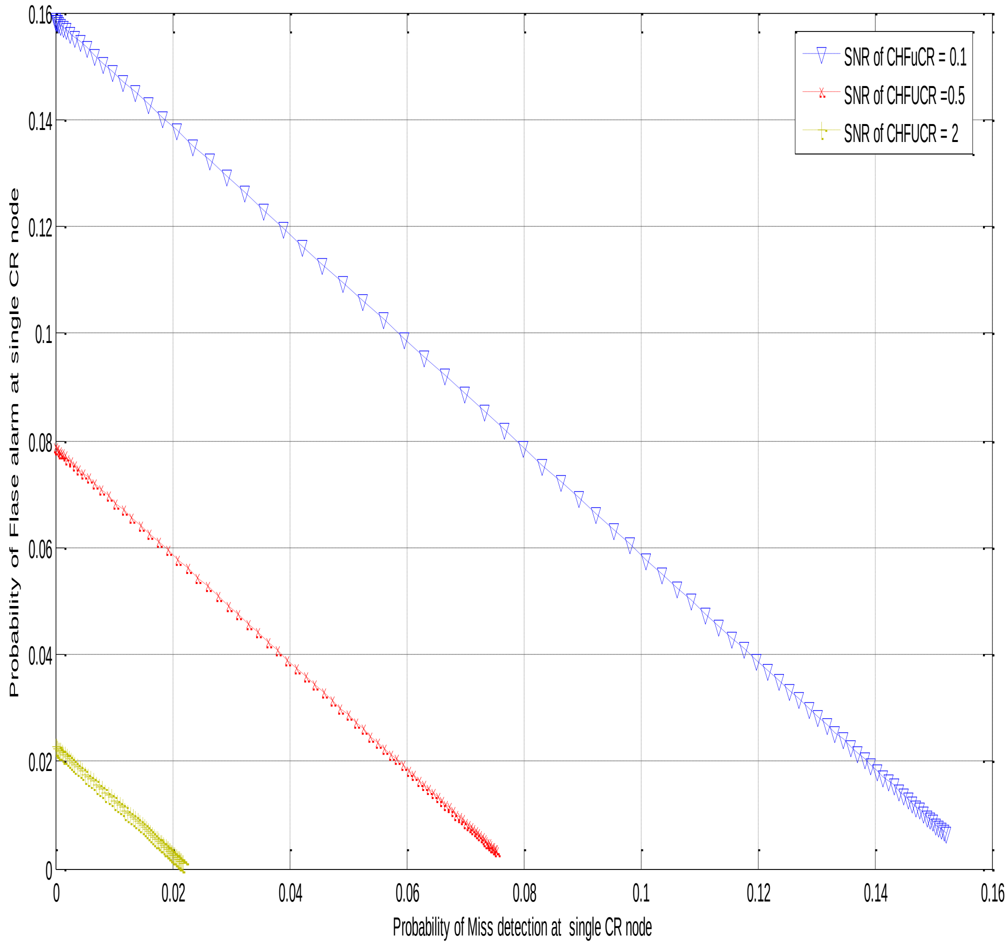


Figure 5-10 Probability of Miss Detection Vs Probability of False Alarm at Different SNR of CHFuCR at CR Node

From the results of Figure 5.10, it is very clear that probability of false alarm P_{ff} is inversely proportional to probability of missed detection, P_{mf}. This means that the probability of miss detection decreases when the probability of false alarm increases. This relation is purely a function of distance between CR node and PU. SNR of the channel CHFuCR has no influence on it.

Simulation results on the variation in probability of detection at CR with change in distance between PU and the fusion centre are illustrated in Figure 5.11 for different SNR conditions.

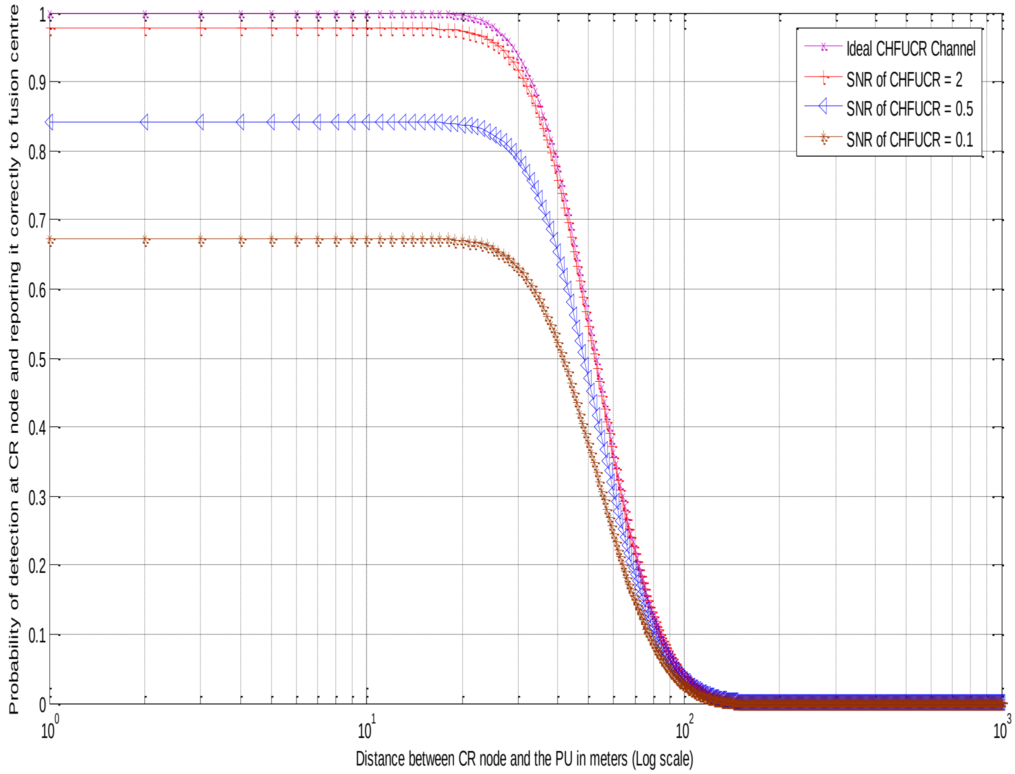


Figure 5-11 Probability of Detection at CR and Reporting it Correctly to Fusion Centre Under Different CHFUCR SNR Condition

As one can see from the results of Figure 5.11, the probability of correct reporting of detection of the presence of PU detection largely depends on the SNR of the reporting channel under ideal conditions. At the edge of the decodability region at distance D, it depends on the log-normal shadowing.

5.3.1 Analysis of Collective Probability Distribution at Fusion Centre

This section presents the collective probability distribution at fusion centre. The variation in probability of missed detection at fusion centre with change in SNR is shown in Figure 5.12.

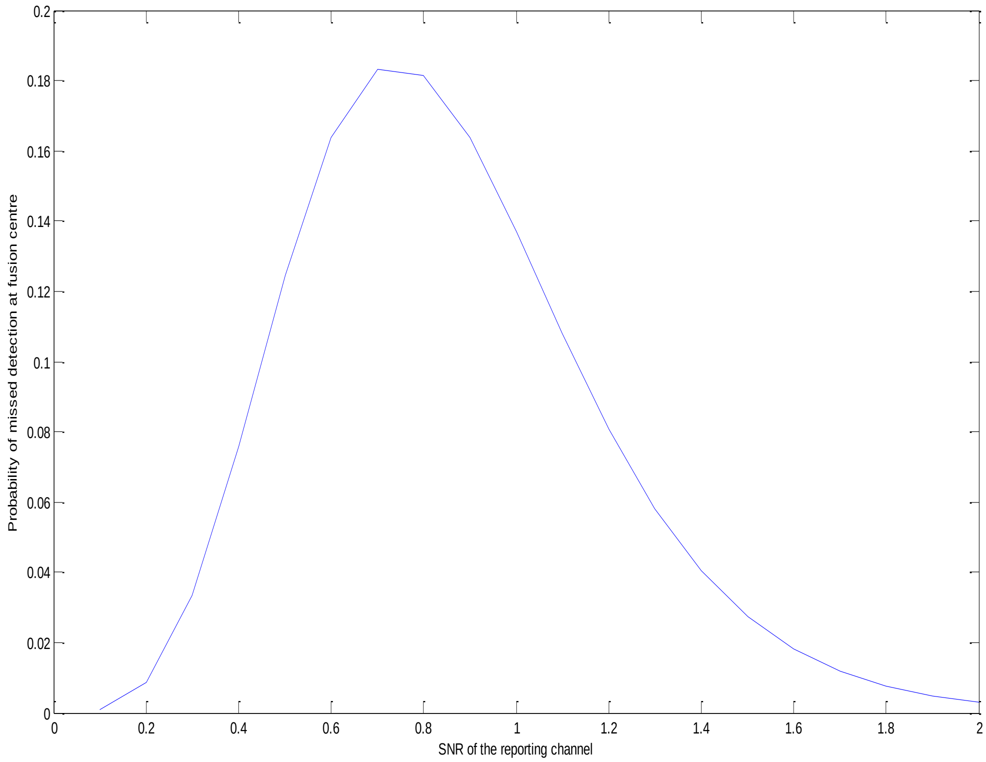


Figure 5-122 Probability of Missed Detection at the Fusion Centre Vs SNR (in dB)

As revealed by the results of Figure 5.12, the probability of missed detection increases irrespective of increase in SNR increase until increase of SNR by 50%. This means that a slight increase in SNR has no effect on probability of missed detection. After that because of improvement in SNR, the probability of missed detection dramatically falls to close to zero. Equation (5.24) is used to simulate the results depicted in Figure 5.12.

Simulation results on the variation in cumulative probability of missed detection at fusion centre with change in cumulative probability of false alarm are presented in Figure 5.13. The simulation results shown in Figure 5.13 are obtained by Equation (5.25).

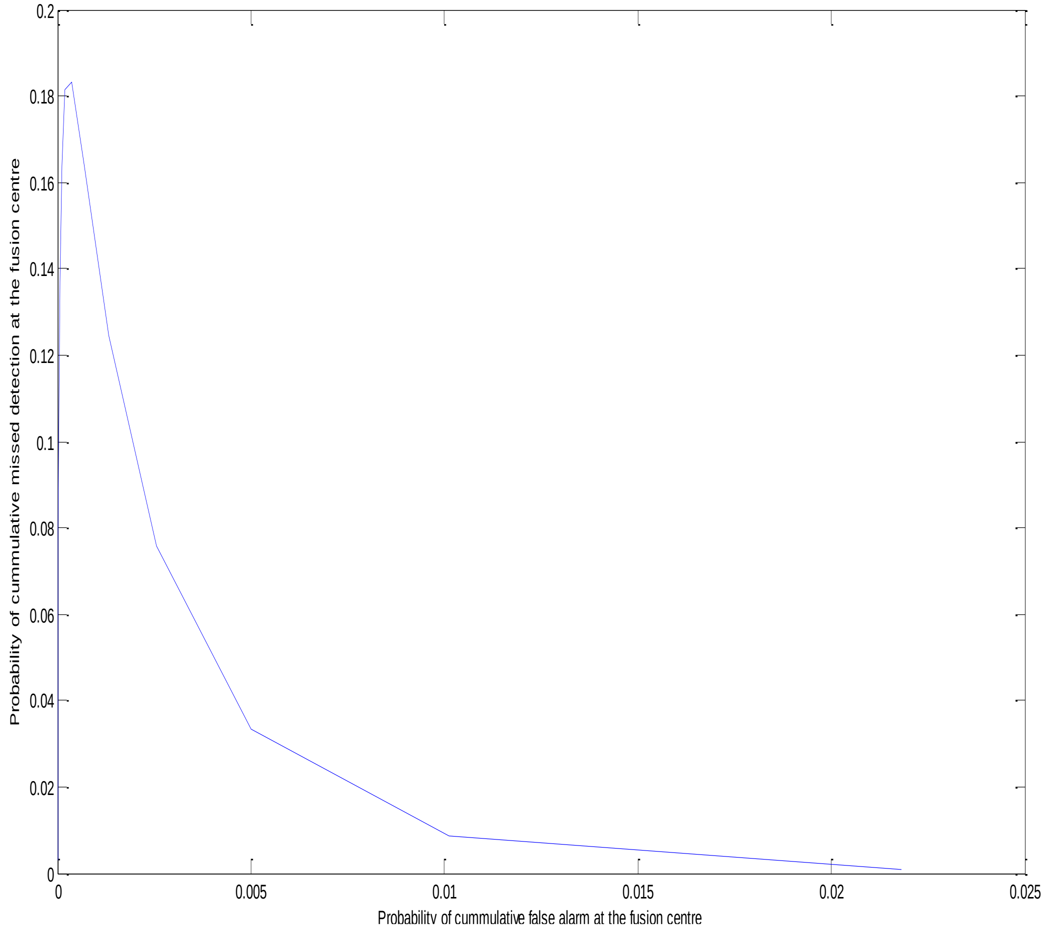


Figure 5-13 Probability of Missed Detection Vs False Alarm at the Fusion Centre

The results of Figure 5.13 indicate that the cumulative probability of missed detection falls with increase in the cumulative probability of false alarm at the fusion centre. As per Neyman-Pearson criteria, the controlled co-operative spectrum sensing cannot minimize both false alarm and missed detection simultaneously. One of them should be specified and then other should be minimized. System applications determine the minimization criteria. If throughput has to be increased, then false alarm should be minimized. If the emphasis is on reduction in interference, then missed detection has to be minimized.

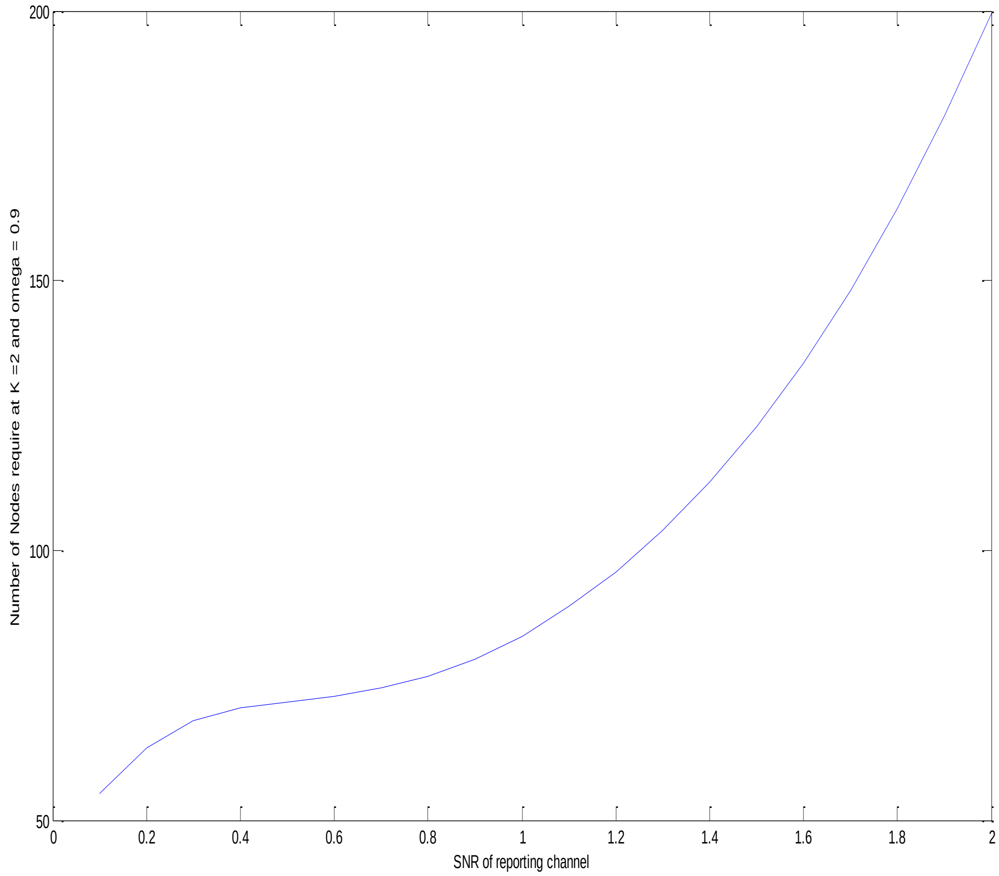


Figure 5-14 Number of Nodes Required for Specified SNR with K = 0.2N

Figure 5.14 shows simulations results when K nodes misses the detection out of N nodes. Case of N = 50, Omega (ω) = 0.9 and K = 10 is considered. Omega is statistical significance threshold. The value of Omega value below 0.9 means statistically insignificant. From the simulation results presented in Figure 5.14, it can be seen that number of nodes required increases with increase in SNR. The number of CR nodes required increases if the noise of decision making has to be reduced at the fusion centre.

5.3.2 Summary of Controlled Co-operative Spectrum Sensing Using Binary Regression on Wireless Path-Loss Curves

Most obvious inference from this model of controlled co-operative Spectrum sensing using regression on wireless path-loss curves is the use of distance as central theme. One can use very basic wireless property like path loss to allocate frequency for communication and frequency for spectrum sensing. Since most important use of spectrum sensing will be to use same spectrum between different networks types, controlling transmit power of CR network based on distance of PU distance from the fusion centre can be very useful. Controlled co-operative Spectrum sensing using binary regression on wireless path-loss curves is an apt choice for application involving the improvement of effective spectral efficiency as described in Equation (3.11).

5.4 Building Blocks of Controlled Co-Operative Spectrum Sensing by CRNode

Basic input and outputs of the controlled co-operative spectrum sensing node is described in Figure 5.15. As shown in Figure 5.15, Channel State Information (CSI) is one of the inputs, which suggests type of channel to be allocated. Distance of the node from the fusion centre is calculated using estimated range of transmit power. Further information on operating frequency band is given by Network Management System (NMS). Mobility information can be obtained by various network protocols like obtaining the home IP of the node or through the network controller.

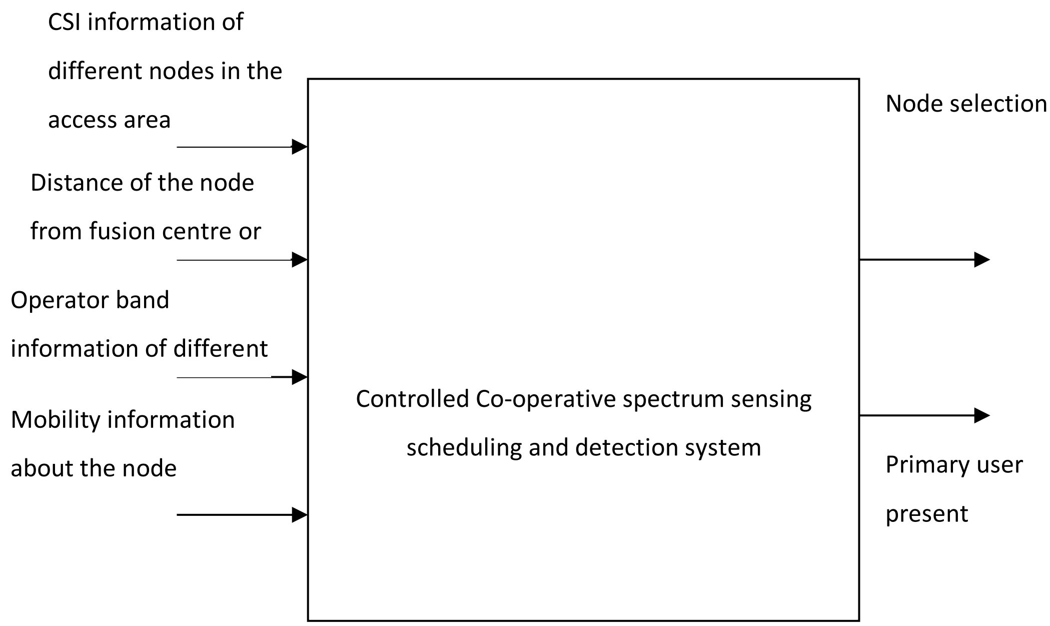


Figure 5-15 Input and Outputs of Regression Based Controlled Co-operative Spectrum Sensing

Operation of the controlled co-operative spectrum sensing and CR system is dependent on two main principles:

1. Co-operative spectrum sensing using the path loss model, known receiver sensitivity, known transmit power of the transmitters
2. Controlling the co-operative spectrum sensing using higher and lower frequency sensing groups using the distance of CR node from the fusion centre

Co-operative spectrum sensing has been addressed in this chapter through modelling and simulation studies. Controlling the co-operative spectrum sensing is more desirable to obtain the optimal allocation of resources for CR communication and CR sensing. Further entire decodability region is divided into higher frequency inner circle and lower frequency peripheral sensing as shown in the Figure 5.16. By this it is possible to achieve better resource allocation as compared to nominal co-operative sensing described in (Yucek T, 2009) and (Ranganathan P, 2006). Further at higher frequency communication of sensing, SNR improves with reduction in distance of communication. This is because higher frequencies have shorter transmission ranges. This will improve probability of detection of PU and hence reduces the false alarm. With increase in probability of detection through improvement of SNR, the interference to PU is reduced and the contribution to interference temperature of PU will be lower. With decrease in the false alarm, throughput of CR network increases thus providing better spectral efficiency.

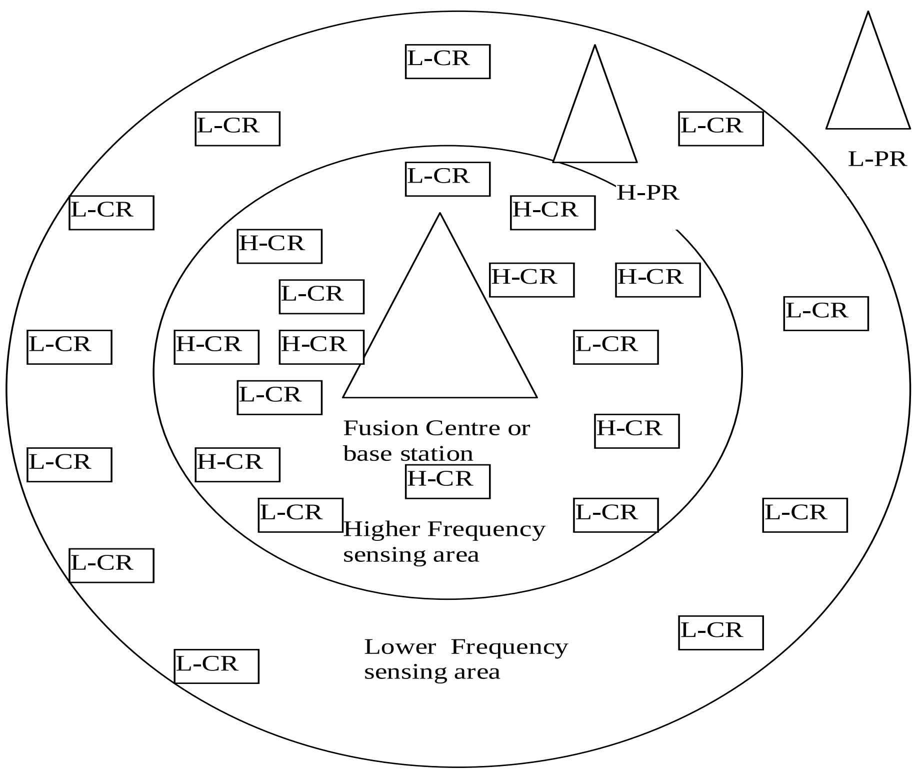


Figure 5-16 CR System Based on High and Low Frequency Sensor Distributed According to the Distance

Following the controlled co-operative spectrum sensing for estimating the distance of PU from the fusion centre and hence approximate distance to CR node, the resource allocation for both sensing and communication will be optimal. However, there is a need to develop algorithm with CSI dependency to provide practical application of controlled co-operative spectrum sensing. Further programmable and adaptive algorithm is highly desirable to apply in real time.

5.4.1 Algorithm for Allocating Frequency of Sensing and Frequency of Communication based on CSI, Distance and Frequency Bands

This sub section presents a discussion on algorithms for allocation of frequencies for sensing as well as frequency for communication. These algorithms are based on CSI.

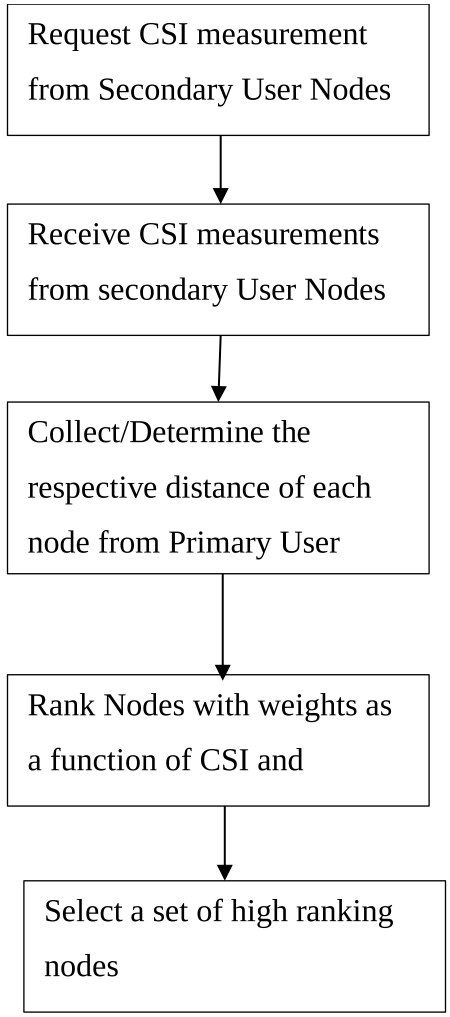


Figure 5-17 Algorithm For Node Ranking at the Fusion Centre

The algorithm for node ranking at Fusion centre is explained through Figure 5.17. After the nodes are ranked, resources for sensing and communication can be allocated as a function of estimated distance and CSI measurements. The decision to be arrived is for the allocation of the higher or lower frequency for communication. Algorithm for determination of presence of multiple PUs using multiband spectrum sensing is explained in Figure 5.18.

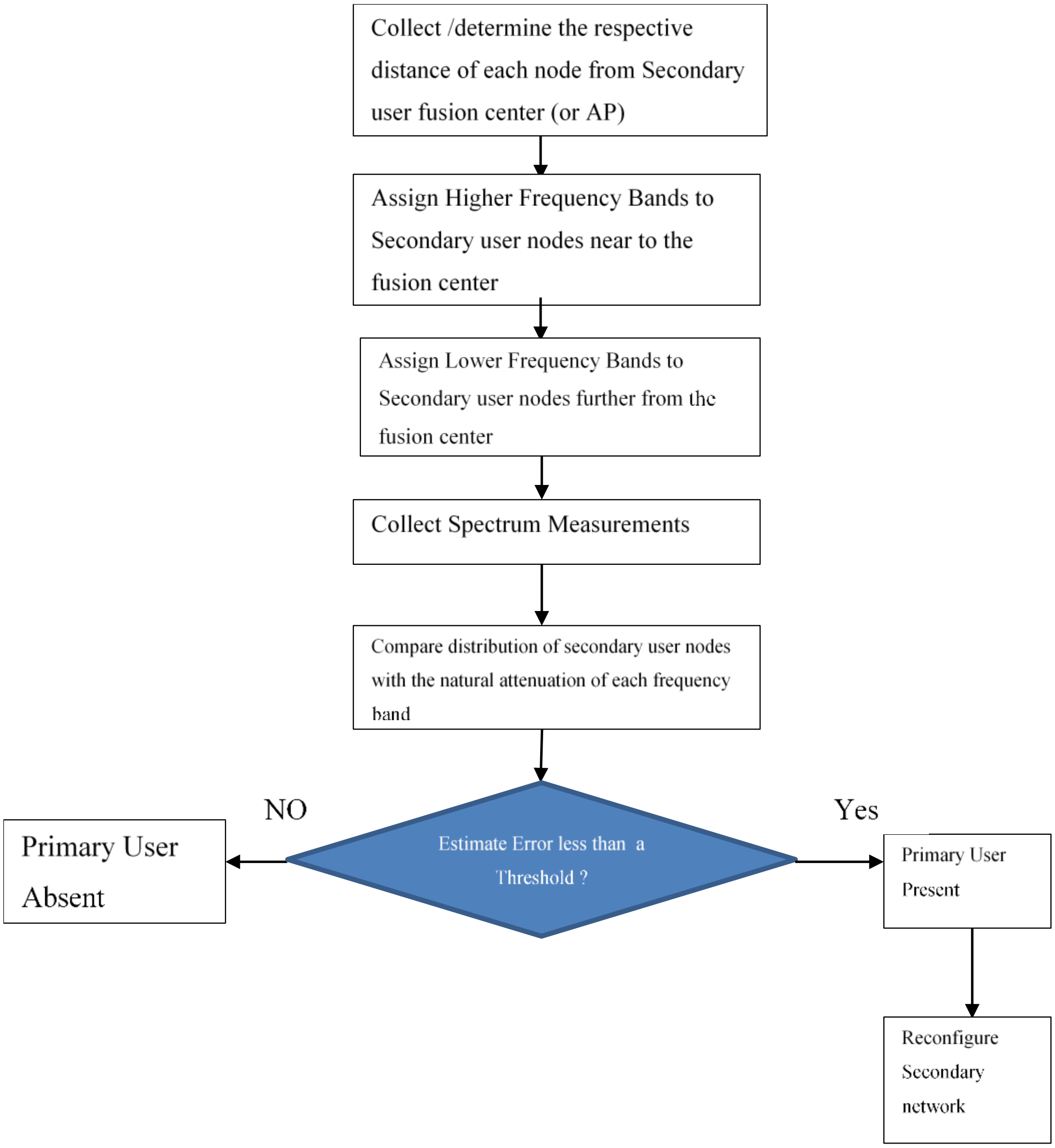


Figure 5-18 Algorithm to Determine Presence of Multiple PUs Using Multiband Spectrum Sensing

Algorithm to assign nodes for multiband frequency sensing based on CSI and distance from fusion centre is explained in Figure 5.19.

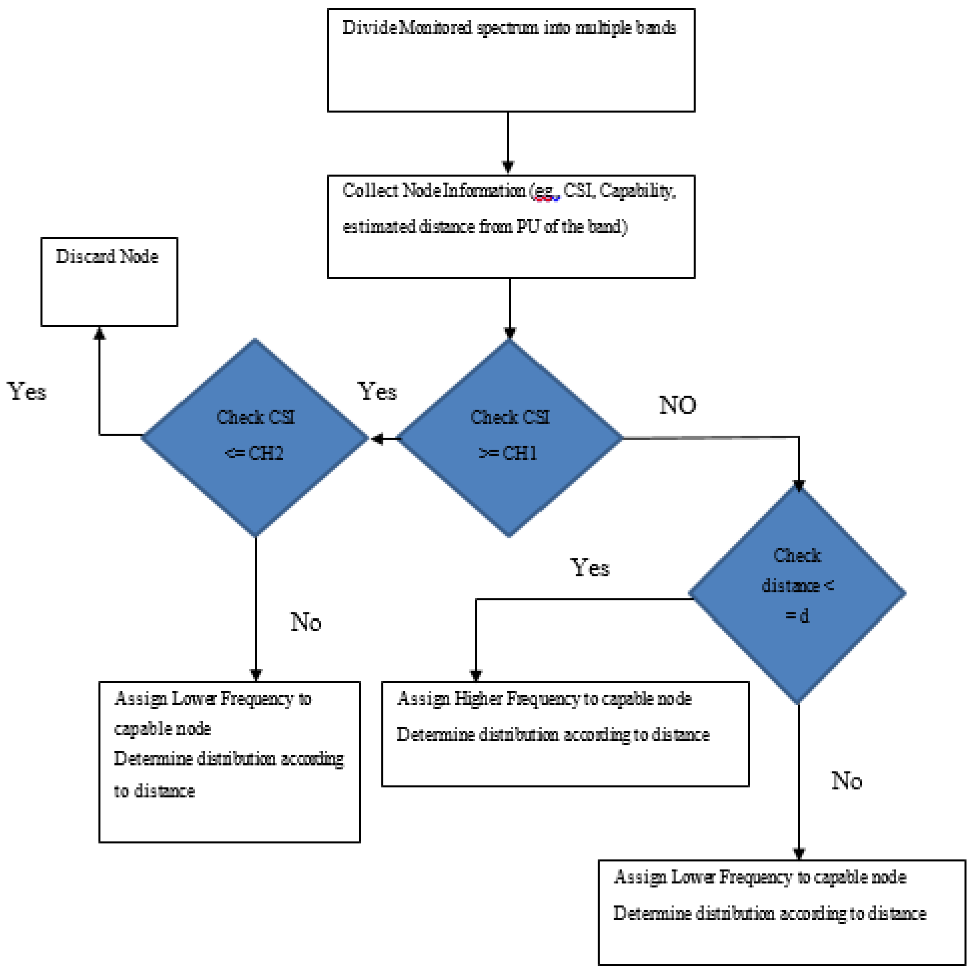


Figure 5.19 Algorithm to Assign Nodes for Multiband Frequency Sensing Based on CSI and Distance from Fusion Centre

Algorithm for allocation of sensing and communication resources in controlled co-operative spectrum sensing. Deterministic CSI of the sensing and probable communication channel of CR system improves the SNR of the system. As shown in the simulation results of Figure 5.9 and 5.10, SNR improves the system probabilities and missed detection by almost half. In the algorithms explained in this sub section, CSI of the CR channel is measured first. Then the distance of the CR node from probable PU is estimated. Then average CSI is obtained. Depending on this information CR nodes are ranked to sense the PU. Highest ranked CR node is allocated for sensing.

5.4.2 CR Operating Region and CR Power Control Using Controlled Co-Operative Spectrum Sensing

The main assumption of the principle behind the proposed controlled co-operative sensing is that sensitivity of receivers of CR node and the PU are known. Since the transmit power of the PU is assumed to be known, it is possible to demark the operating region of the CR within known dynamic bound of space, frequency and time. From the co-operative spectrum sensing, the approximate distance of PU from the fusion centre is known. Therefore, the transmit power of CR should be allocated in such a way that it has almost zero interference with the PU.

Distance ‘dp’ of the PU from the fusion centre is known through the equation:

$$\mathrm{Rx(Power)} = \mathrm{Tx(Power)} - (\mathrm{PL(d0)} + 30\log(\mathrm{dp/d0})) \tag{5.38}$$

Equation (5.38) can be rewritten as:

$$(\mathrm{Rx(Power)} - \mathrm{Tx(Power)} + \mathrm{PL(d0)})/30 = \log(\mathrm{dp/d0})$$

$$\mathrm{dp(transmit)} = (10\text{^}(\mathrm{Rx(Power)} - \mathrm{Tx(Power)} + \mathrm{PL(d0)})/30) * \mathrm{d0} \tag{5.39}$$

If the same path loss model applies to CR node also, the transmit power of CR is given by:

$$\mathrm{Rx(PowerPri)} = \mathrm{Tx(PowerCR)} - (\mathrm{PL(d0)} + 30\log(\mathrm{dp/d0})) \tag{5.40}$$

Rx(PowerPri) should be less than sensitivity of the PU. Therefore,

$$\mathrm{Rx(Prisensitivity)} > \mathrm{Tx(PowerCR)} - (\mathrm{PL(d0)} + 30\log(\mathrm{dp/d0})) \qquad (5.41)$$

$$\mathrm{Tx(PowerCR)} < \mathrm{Rx(Prisensitivity)} + (\mathrm{PL(d0)} + 30\log(\mathrm{dp/d0})) \qquad (5.42)$$

It is also necessary to make sure that sensitivity of the CR node is much lower than the sensitivity of the PU. The operating region and the dynamic TX power control of CR node can be depicted in the following manner shown in Figure 5.20.

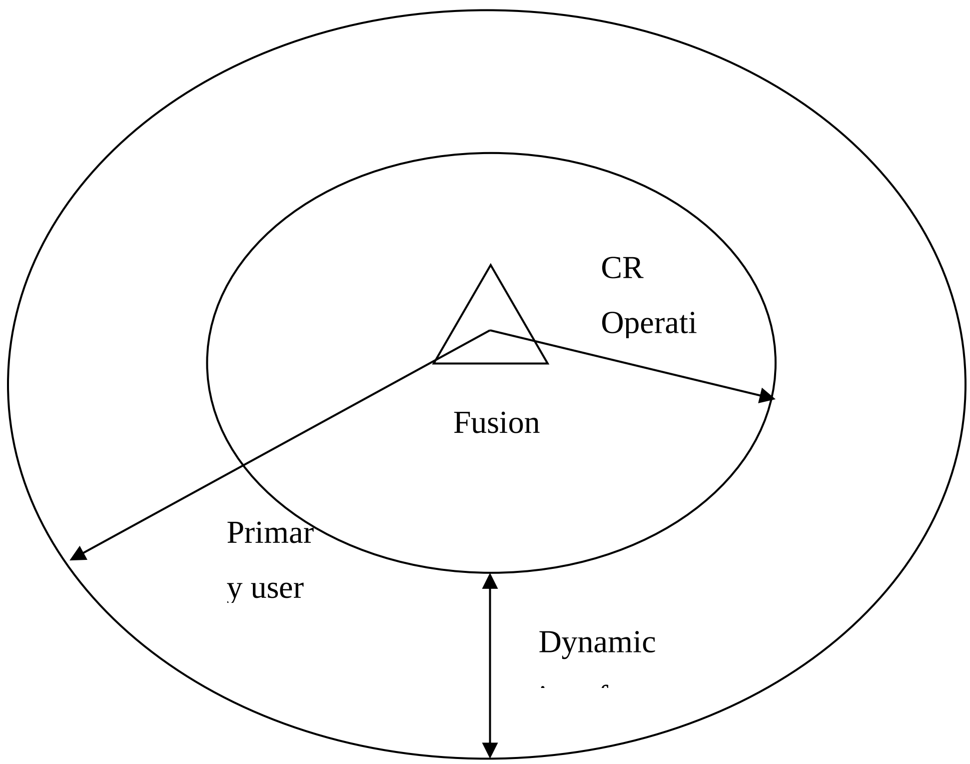


Figure 5-20 CR Region of Operation Using Transmit Power Control (TPC)

5.4.3 Opportunities of Improvements to Controlled Co-Operative Spectrum Sensing

Although controlled co-operative spectrum sensing greatly improves available spectrum for communication, it does have limitation in terms of macro visibility of spectrum holes. Spectrum holes cannot be communicated across the network nor can it be exploited between the subnets. Another serious drawback is the hypothesis of the path loss model to measure the presence of PU. However, this may not be best possible hypothesis to exploit spectrum holes. In addition, hypothesis based on path loss model is rather static and cannot be applied across time, space and frequency. It is a typical space and frequency only model (based on only distance and frequency). This hypothesis does not consider the time aspect of spectrum hole.

Following aspects can be considered for future work pertaining to power control of CR transmission:

1. Relation between sensitivity of PU and sensitivity of CR.
2. Dynamic interference budgeting
3. CR Tx power in terms of interference, CR sensitivity and sensitivity of PU
4. Block diagram of the CR modem
5. Multiband CR detection

5.5 Summary

This chapter has presented a new concept of controlled co-operative spectrum sensing using binary regression on wireless path-loss curves. Using controlled co-operative sensing, the distance of the PU from the fusion centre can be accurately estimated, with an assumption that the PU is operating conforming with standard defined mobile terminal specifications. With estimated distance using techniques defined in this chapter and algorithm for allocation of resources, the SNR of the sensing channel is improved over conventional co-operative spectrum sensing. As shown through the simulation results, with improvement of the SNR, false alarm drops, and this improves the throughput of CR network. Also incorporating this improvement in Equation (3.11). 50% improvement in the spectral efficiency is evident with controlled co-operative sensing relative to the spectral efficiency obtained through conventional spectrum sensing technique. This chapter has also discussed cumulative probabilities at the fusion centre. An expression for the determination of the optimal value of CR nodes ‘N’ required for co –operative spectrum sensing to meet the specified threshold of statistical significance is also derived. An algorithm for allocating frequency for sensing and frequency for communication based on CSI, distance and frequency bands is also explained in this chapter. By using the distance based assignment of CR communication, there is an increase in total available bandwidth and total usable bandwidth. Increase of total usable bandwidth in Equation (3.11) will increase the spectral efficiency linearly. Thus, by assigning higher frequency to shorter distance CR communication and high quality low frequency bandwidth to longer distance communication, the total usable bandwidth increases by 50%, with this feature, the spectral efficiency CR enabled network increases by 50%. This chapter also presents an algorithm to assign nodes for multiband frequency sensing based on CSI and distance from fusion centre. This chapter has also discussed the operating region and power control of CR nodes using controlled co-operative spectrum sensing. Such an analysis will result in minimization of interference at PU. This chapter also highlights the research opportunities for possible further improvements in controlled co-operative spectrum sensing.

Summary of performance improvements with controlled co-operative sensing is presented in Table 5.1. The results depicted in Table 5.1 clearly substantiate the performance improvement with controlled co-operative sensing expressed through 5 performance metrics. Usable bandwidth for CR increases due to estimation of distance of PU from fusion centre. By estimating distance, 700 MHz (lower frequency band) can be allocated to a CR node located at a larger distance and higher frequency band (2.5 GHz) can be allocated to a CR node present at a shorter distance. The full usage of frequency bands for appropriate range of communication and sensing increases the SNR (Theodore S. Rappaport, 1996). Improved SNR of sensing channel leads to reduction in the probability of false alarm and probability of missed detection (from Equations 5.24 and 5.25). With the increase in both SNR and probability of detection, probability of missed detection decreases. Therefore, lesser number of nodes is required in the co-operative spectral sensing to detect PU. This in turn reduces the bandwidth required for sensing.

Table 5-1 Performance Comparison with and without Controlled Co-operative Spectrum Sensing

Performance metrics	**Without controlled co-operative spectrum sensing**	**With controlled co-operative spectrum sensing**
Usable bandwidth for CR	100 MHz	250 MHz
Range of Probability of false alarm at fusion centre	0.3 to 0.1	0.1 to 0.01
Range of Probability of missed detection at fusion centre	0.3 to 0.1	0.15 to 0.01
Number of nodes require in co-operation for false alarm and missed detection of 0.1	>500	< 100
Effective spectral efficiency	10 bits/sec/Hz	25 bits/sec/Hz

Chapter 6 - 3D Spectrum Detection and SVM Based Macro Spectrum Hole Detection

This chapter proposes the concept of 3-Dimensional spectrum sensing as a significant improvement over conventional 1-D spectrum sensing. The proposed 3-D spectrum hole detection considers time and space in addition to frequency domain. With resource map available to infrastructure-based network, allocation of resources to CR communication is better with 3-D structures when compared to 1-D or 2-D structures. This chapter also presents a generic setup for 2-level spectrum hole detection using macro and dynamic spectrum hole detection. The same model is applied to all the 3 domains of 3D spectrum hole detector. Support Vector Machine (SVM) with 3D RBF kernel is used to estimate the spectrum holes. This chapter defines the system level probability of missed detection and probability of false alarm applicable for 3D spectrum sensing. The missed detection in 3D-spectrum hole detector is a combination of 3 variables and has 3 degrees of freedom. Based on the comparison the derived equations with 3D and 1D detection, this chapter concludes that 3D spectrum hole sensor exhibits lower missed detection leading to a reduction in interference temperature at PU. As a figure of merit in the assessment of improvement in the spectral efficiency because of CR enabled network, a term called CR gain is proposed in this chapter.

6.1 Introduction

The research study presented in thesis brings about Novel architecture and implementation methods of CR based heterogeneous networks. Spatial resource exploitation has given way to a number of ground breaking wireless architecture like cell based mobile communication using frequency reuse. Similarly, a novel way of using time, frequency and codes has provided various 2G technologies. Further exploiting orthogonal property of code and frequency has given rise to 3G and 4G networks. CR technologies are expected to be very agile in structure and resource usage. Interference is the key concern in the CR based networks. If network is heterogeneous (this means many types of air interfaces and networks trying to access the same radio resources), then demand type for resources is also heterogeneous. This requires very nimble/dynamic resource allocation. Agility of resources also requires robust margin for error. Distance vector based association of sensing frequency and CR communication resources (time, space, and frequency) would provide this margin of error in CR systems that can enable practical deployments. However, challenge exists at infrastructure and devices interface, where infrastructure must provision the D2D setup based on statistical models in space, time and frequency domains, such that there is almost zero interference probability to PU.

This chapter defines the interfaces between infrastructure and device which acts as both PU on one interface and D2D device on other interface, using controls from base station of infrastructure network. This is possible because infrastructure will be aware of the possible interferences early and more precisely, since infrastructure will be used to setup both D2D as well as PU networks. Further this provides practical deployment because it supports prospective business model of operators, who can discount D2D communication in 700 MHz or cellular band using CR technologies.

6.2 Brief Review of CR Enabled Networks

Recent times have witnessed a substantial progress in CR. (Brett Kaufman, 2013) suggests overlaying the D2D network on 4G networks and limiting interference temperature to minimize the interference to PU. (Nagendra Nagaraja et al., 2014) suggest a scheme of using distance vector to assign frequency of sensing in co-operative spectrum sensing, which this research further enhances to derive 3D spectrum sensing. (Wellens, 2009) analyses the spatial statistics of spectrum usage. But time and frequency parts were not explored to the fullest extent. (B. L. Mark, 2008) and (R. Tandra, 2008) suggest basic definition of spectrum hole. In this thesis, the definition of spectrum hole suggested in (R. Tandra, 2008) is adopted.

6.3 System Model for Heterogeneous CR Enabled Network

A system model for heterogeneous CR enabled network is illustrated in Figure 6.1. It describes heterogeneous network, with two level CR detection. The D2D communication is overlaid on infrastructure based network.

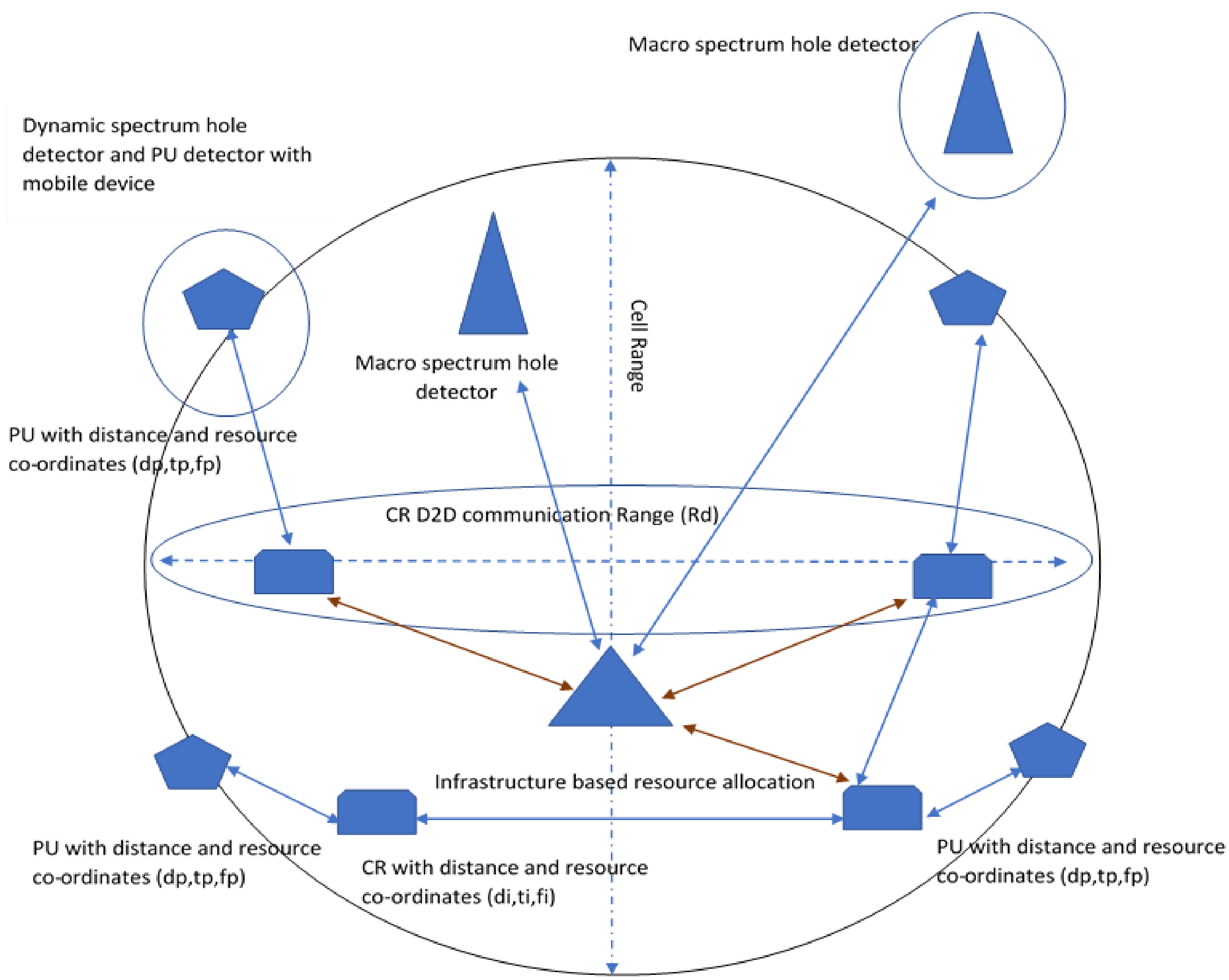


Figure 6.6-1 CR Enabled Heterogeneous Network with D2D Overlaid on Simple Cellular Network

The spatial parameters come with two ranges, one is cell range and other is CR D2D communication range. The control plane is divided into CR control plane containing CR control channels, CR sensing channel and infrastructure control channels. The data plane of the network is again divided into CR data channels and infrastructure data channel. The communication resources are defined for CR network in terms of distance, time and frequency (d, t, f). Defining the CR communication resource in 3 dimensions provides greater degrees of freedom to provide spectrum agility for CR communication. Also switching to newer resources can be very granular, when differential agility (Δd, Δt, Δf) is very fine tuned and optimizable as per the CR communication requirement with minimalizing interference to Infrastructure network.

6.4 Spectrum Resource Assignment for CR Usage

Spectrum resource is defined in the co-ordinates of distance, time and frequency (d, t, f,). It is important to have this view of spectrum resource rather than simplistic frequency view to obtain maximum efficiency from spectrum agility. Spatial presence of PU is estimated by the PU detection decision regression on pathloss models.

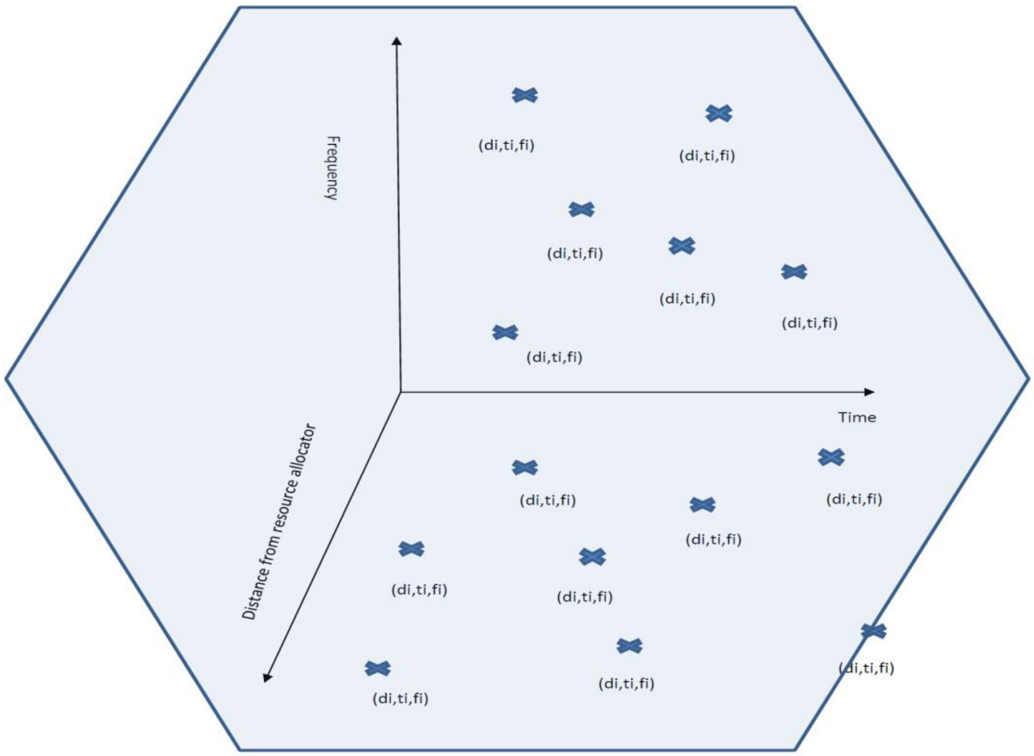


Figure 6-2 Resource Map at the Cognitive Radio Resource Allocator

Temporal estimation is obtained by the statistical data of PU usage in a location and in a frequency band. Frequency of CR communication is determined by CR requirement as well as spatial and temporal PU presence estimation. The central resource allocator will have information about different resources available for CR communication. Typical resource map of the CR communication resource is shown in Figure 6.2. In Figure 6.2, ti is the time slot of the resource availability. fi is the frequency band or individual frequency resource that is available. di is the distance from resource allocator.

There can be two types of resources in a heterogeneous network:

1. $R_{is}(d_i, t_i, f_i)$ used by CR to use infrastructure based network through base station

2. Rd2d(d_d, t_d, f_d) used by CR for D2D (or P2P) communication without relying on the infrastructure for data channel, But setup or control is provisioned by the infrastructure initially

Very nature of classification of resource type describes the heterogeneity in the network topology. (Brett Kaufman, 2013) describes the D2D overlay on the cellular network. But it is still more of two network architectures and it does not act as single heterogeneous network with central resource allocator. Single heterogeneous network will have more appeal to infrastructure service provider to enable free CR based D2D communication and charge for base station to device communication in case multi-hop communication required. This makes proposed CR enabled heterogeneous network architecture to be practically implementable and acceptable to service providers, rather than two network architectures, where network service provider is in constant conflict with CR interference possibilities. Also, the same device being PU for device to base station communication and CR for D2D communication is an appealing application of CR.

6.5 3D Spectrum Hole Detection Algorithm

Review of prior research on spectrum sensing in CR reveals many techniques for the detection of frequency occupancy of the PU. In this research, strategy is to find the spectrum holes in terms of the distance, time, and frequency (d, t, f) using networked infrastructure and use them for CR usage for D2D communication as well as protecting PU from any CR interference. Spectrum hole is estimated by deploying spectrum hole detectors across space, time and frequency domains as shown in Figure 6.3. Time factor can be statistical estimate and one can assign probability of occupancy through the expected usage model. Spatial spectrum hole detection and power control are derived from Estimated Distance Based Resource Allocation (EDBRA) and Estimated Distance based

Power Control (EDBPC). Frequency spectrum hole detection is performed by obtaining the frequency bands which has no PU occupancy seen.

Frequency band is divided into lower frequency bands and higher frequency bands to form Wideband Co-operative Spectrum Sensing (WCSS). Different sensing frequencies are allocated according to distance from base station. Devices which are furthest distance from base station are allocated to detect high frequency spectrum and the devices that are nearer to the base station are allocated the task to detect lower frequency. With these temporal, spatial and frequency spectrum hole detection combined and along with D2D power control, overall chance of obtaining spectrum for CR D2D communication increases and probability of interference to PU usage decreases.

Further each of these detectors can be classified into dynamic and macro detectors. The dynamic detectors are used to detect the spectrum hole in space, time and frequency as they occur. Macro detectors are used to obtain large scale spectrum hole depending on the network macros like area of spectrum idle, time of spectrum idle and a frequency of spectrum which is idle for long duration of time and in an area.

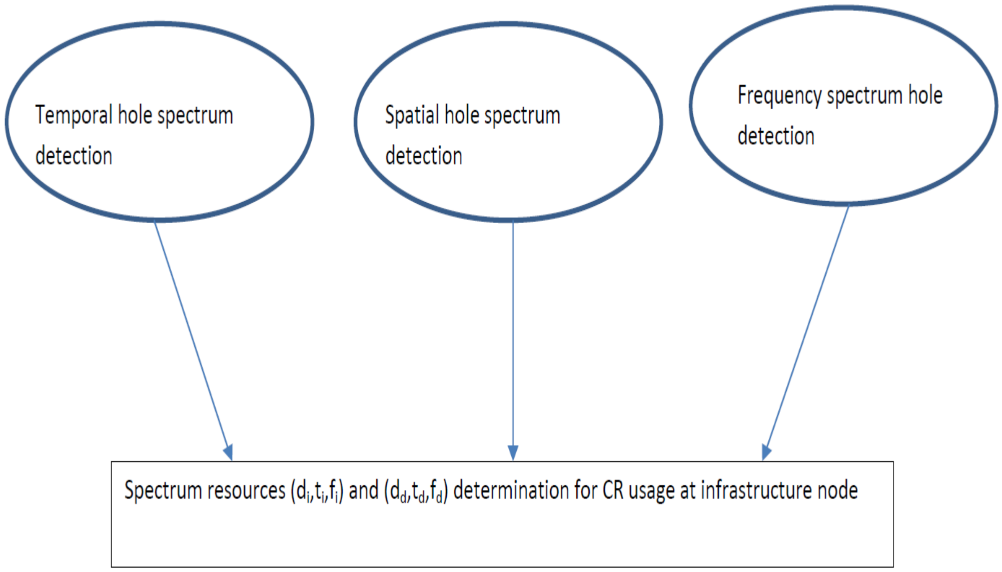


Figure 6-3 Spectrum Hole Detector

The dynamic detectors are within D2D module or D2D chip of the Mobile device. Macro detectors are typically a network element within the infrastructure based network. Macro detectors are information processing elements which extract network statistics and identify spectrum holes with high probability.

Typical communication module architecture of the D2D chip is given in Figure 6.4. In addition to usual Receive and transmit chains, the communication module contains spectrum sensor.

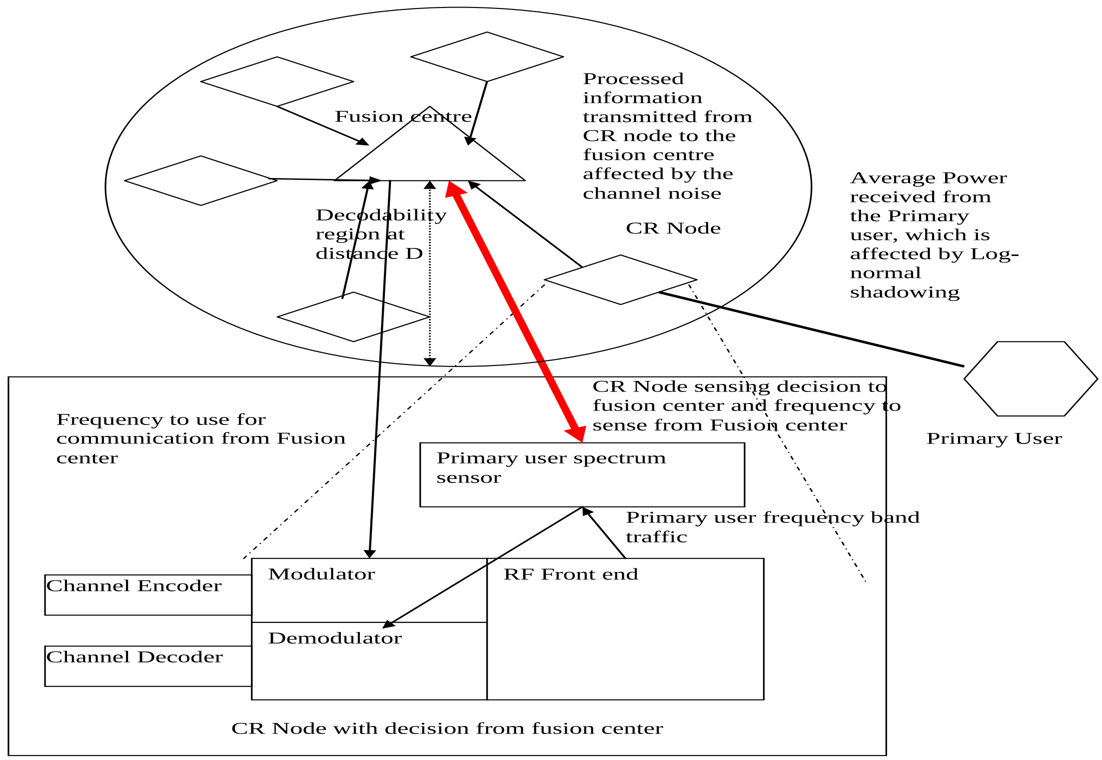


Figure 6-4 D2D Communication Module in the D2D integrated Circuit

Spectrum sensor can be energy based or more advanced cyclo-stationary based.

6.5.1 Dual Layer of Spectrum Hole Detection in 3 Dimensions

The generic setup for 2-level spectrum hole detection using macro and dynamic spectrum hole detection is shown in Figure 6.5. Same model is applied to all the 3 domains of 3D spectrum hole detector. Support Vector Machine (SVM) with 3D RBF kernel is used to estimate the spectrum holes. 3D RBF is used to transform the data samples collected from domain comprising space, time and frequency and then convert it to feature space.

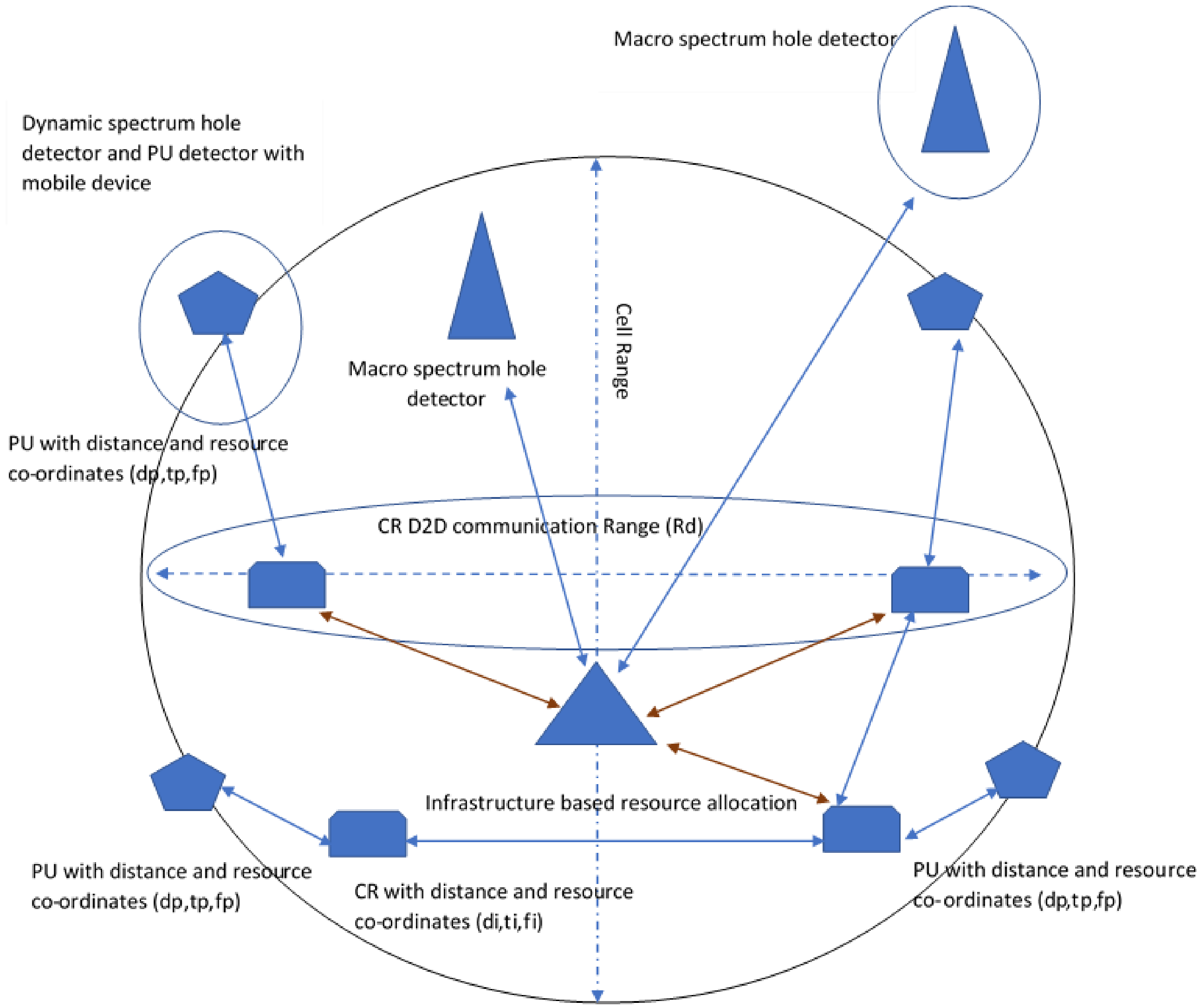


Figure 6-5 Typical Wide Area Heterogeneous Network with Two Level of 3D Spectrum Hole Detection with Macro Spectrum Hole Detection using a Network Element and Dynamic Spectrum Hole Detection Using the D2D Spectrum Hole Detector Module

Macro statistical model can be based on decision taken by D2D spectrum hole detector and transmitted to network element with R_{d2d} (d_i, t_i, f_i) indexing. Each of this detected hole in the 3 dimensions are stored in the database. By using data mining of the database, one can retrieve a few of these resource entities with high probability. Apart from this, specific model pertaining to space, time and frequency can be deployed which provides D2D resource map with high probability. So basically, one can define macro statistical model based on training of decision from the D2D spectrum detector or based on the domain specific models such as HMM (for time), Semivariogram (Space) and regression on path loss model (distance and hence Frequency). Each statistical model is described in detail and probability of false alarm as well as missed detection are arrived based on statistical nature of these models considering the effect of feedback from D2D dynamic hole detection and the detection of PU.

The output of the spectrum detector is given in the Table 6.1. Output contains Resource co-ordinates in terms of Rd, resource range in-terms of ΔRd^3 and probability of primary user occupying the Resource Rd in terms of range ΔRd^3. One can have a mean value of probability if ΔRd^3 is small or the distribution of probability if ΔRd^3 is large. For CR device being used for D2D communication, it is possible to use mean value of the probability rather than probability distribution across the spear of range.

Table 6-1 Output of Dual Layer 3D Spectrum Detector

Resource name Rd(d,t,f)	Expected operating range of CR D2D device, ΔRd (Δd, Δt, Δf)	Probabilities of primary user usage within the band(P_{pri})
Rd1	$\Delta Rd1^3$	$P_{pri}1$
Rd2	$\Delta Rd2^3$	$P_{pri}2$
Rd3	$\Delta Rd3^3$	$P_{pri}3$
.	.	.
.	.	.
.	.	.
Rdn	ΔRdn^3	$P_{pri}n$

Range of operation of the D2D device ΔRd (Δd, Δt, Δf) is estimated using know transmit power of PU and estimated required transmit power of secondary user. The estimated range is assigned to be outside the no-talk zone of infrastructure network. In (R. Tandra, 2008) no-talk is sorted depending on the knowledge of PU. This is an oversimplification of problem with elimination of most important function of network management. Figure 6.6 depicts the model for detection of 3D spectrum hole with the defined probability of PU usage within a specified range.

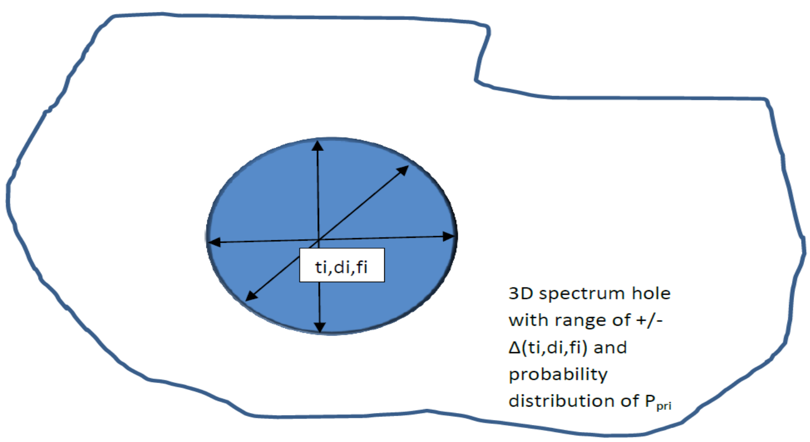


Figure 6-6 Example 3D Spectrum Hole with Defined Probability of PU Usage within the Range, Range of Operation of D2D device in Terms of Distance, Frequency and Time

One can also utilise the model depicted in Figure 6.6 to find out resources which are outside no-talk zone currently and just use it. This can be possible if one maintains the hashes of resources in one coordinate with mapping to other two co-ordinates. For example, it is possible to search resources at current location or duration of time or in a frequency band. Once this scanning is completed, resource can be scheduled for usage by D2D device. Algorithm for the resource allocation by the base station for D2D request is as follows:

The following mapping can be defined as shown in Figure 6.7.

$\Phi\ () :(\Delta d, \Delta t, \Delta f) \rightarrow H$

Where, H is a feature space. As a result there is a 3-dimension data space, Δd is the distance vector and (Δt, Δf) denotes time and frequency bands at which the spectrum is not used by the PU. It is possible to choose Φ () as 3D RBF Kernel. Applying this, simple RBF kernel in 3 dimensions can be used.

$$\emptyset(X) = \exp\left(-\gamma|x - \grave{x}|^2\right) \tag{6.1}$$

Where γ is a non-zero constant, x is the dataset and x` is the estimated value. The prediction results from SVM in these dimensions are combined to obtain resource map for D2D. The generator for each data is 3 dimensional. For each (x, y, z) in space, there is a corresponding (Δd, Δt, Δf). Thus, by applying SVM directly on Δd, Δt and Δf, the analysis can be reduced from 3 dimensions to 3 one -dimension data since space, time and frequency resource availability are independent of each other.

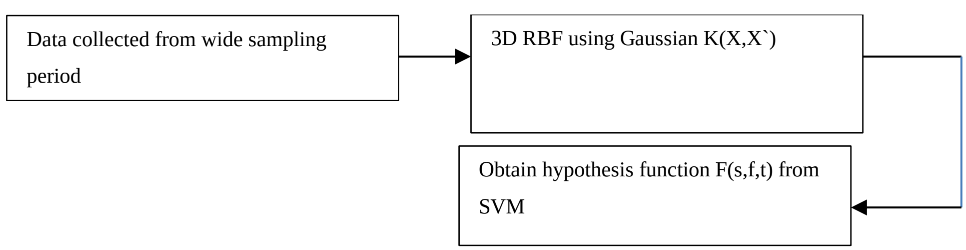


Figure 6-7 Working with RBF Kernel for SVM

SVM provides probability for each expected hypothesis in each domain. So, for a given sphere of radius Δd, there is a probability triplets (P_d, Pt, P_f). Enhancing throughput (spectral efficiency of combined network) and minimizing D2D interference to PU will involve maximizing these probability triplets (P_d, P_t, P_f). While applying 3D RBF kernel, 3D vector which provides resource map described earlier will be identified. The algorithm for detecting the presence of the PU is described in Figure 6.8.

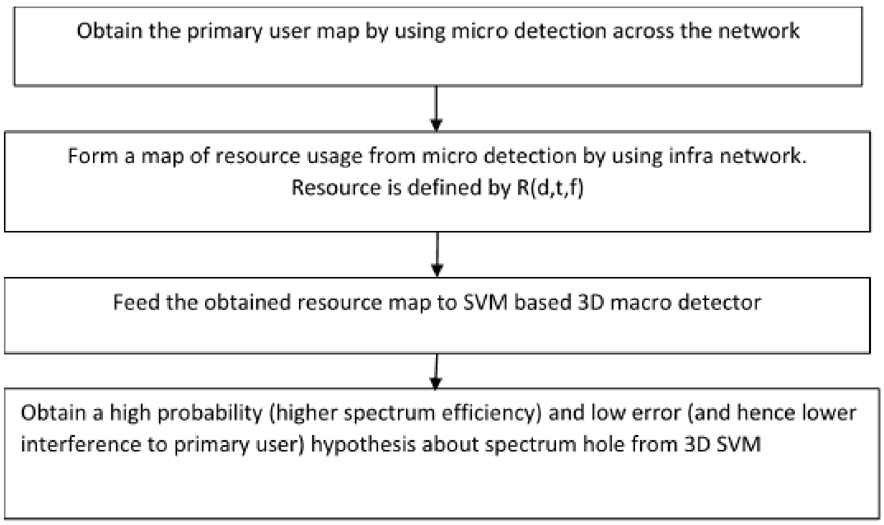


Figure 6-8 Data Collection and Macro Hypothesis Detection using SVM in Actual D2D Overlaid on the Heterogeneous Network

The obtained macro hypothesis is a function in the 3D macro detector over (Δd, Δt, Δf), which can be written as f (Δd, Δt, Δf). Hypothesis can change in space, frequency band and time. But assumption is that it will be stationary enough to exploit the hypothesis, which are given by Δ over each dimension. However, for simulation, micro detection is modelled separately for time, space and frequency using Hidden Markov Model (for time), Semivariogram (space) and Gaussian (for frequency). These three source generators are combined to form a vector of (Δd, Δt, Δf) in python simulation setup (Figure 6.9). With these 3 separate sources, the spectrum usage can be accurately modelled.

Considering the random distribution of unused space, time and frequency resources, one can have the distribution as shown in Figure 6.10. But however in the measurement of wireless spectrum utilization in a real scenario, spectrum holes are distributed across time, frequency and space as close to HMM, Gaussian and Semivariogram as reported in (Wellens, 2009) and (B. L. Mark, 2008). Therefore, there is a need to train the 3D SVMs according to these distributions, individually and apply models in 3D detection to get cumulative detection.

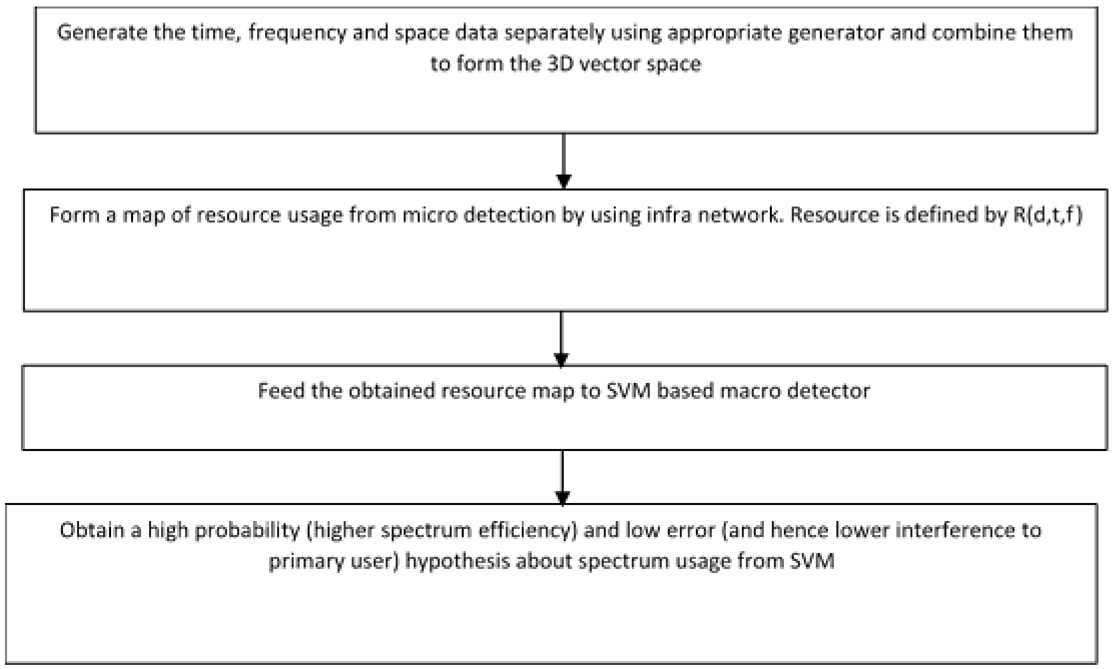


Figure 6-9 Simulation Setup for SVM Based Macro Hypothesis for Spectrum Usage

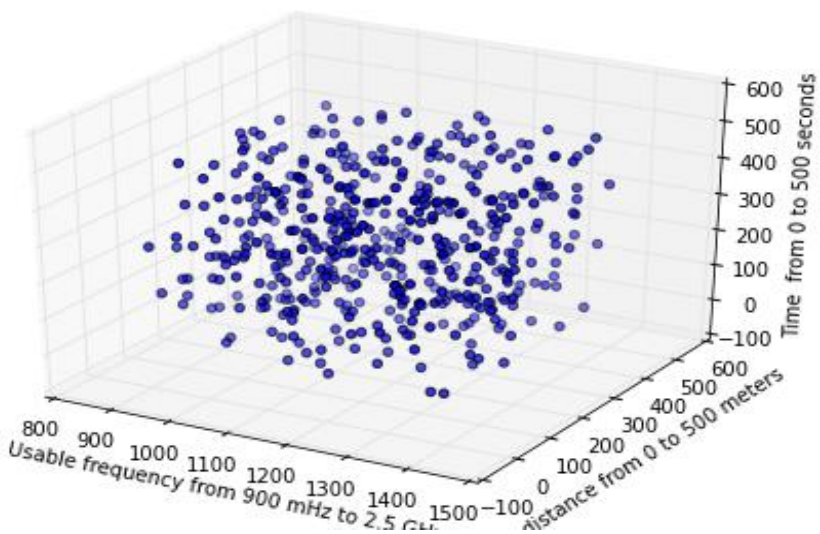


Figure 6-10 Spectrum Holes Considering Random Distribution in all 3 Dimensions

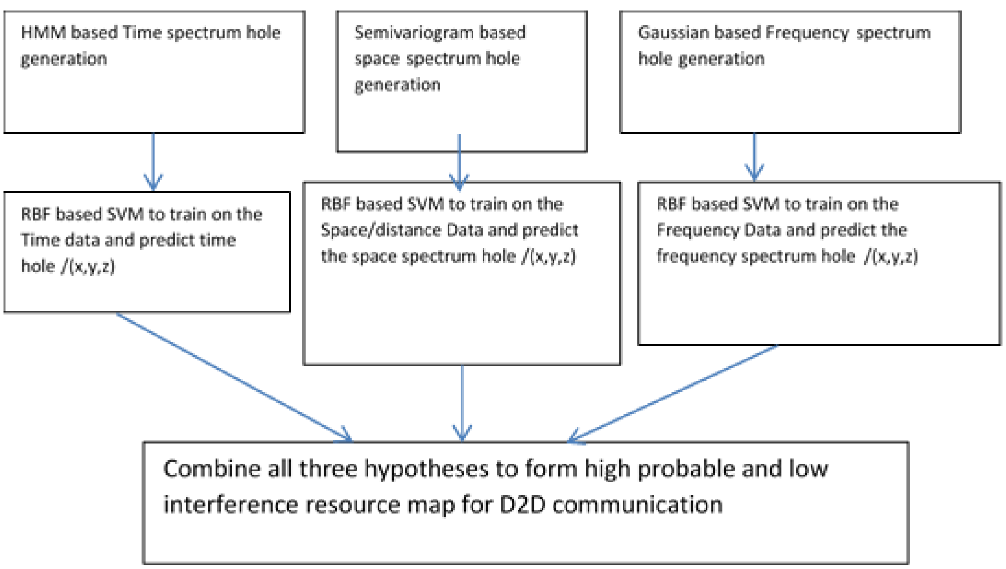


Figure 6-11 Python Based Simulation Setup for Obtaining Highly Probable Hypothesis for 3D Spectrum Hole Detection

Data generation for the simulation is obtained from 3 sources namely time, frequency and distance vector. For time-based spectrum hole, Hidden Markov Model (HMM) is used based on duty cycling. For distance/space vector, Semivariogram is used as indicated in (R. Tandra, 2008). For frequency, Simple Gaussian across the space is used. Overall setup for simulation is shown in Figure 6.11.

6.5.2 Temporal Spectrum Hole Detection

In real deployment of CR, temporal spectrum hole sample is obtained using big data server located in Network Management System (NMS). No distribution is assumed. Distributed temporal spectrum sensors provide their inputs to NMS. This is combined at NMS using majority rule and forms temporal resource map across space and frequency band. As stated in (Wellens, M, 2009), one can use Hidden Markov Model to model the duty cycle of the spectrum occupancy. For the lack of field data, time duty cycle is modelled using first order HMM. Figure 6.12 shows the time distribution of the spectrum hole across the frequency band.

Figure 6-12 Time Based Spectrum Hole (Red → Occupied, Blue → Empty)

6.5.3 Spatial Spectrum Hole Detection

In a real deployment setup spatial spectrum sensing, spatial spectrum hole information is obtained using distributed spectrum sensors, which would send the spatial hole information to NMS, through cooperative spectrum sensing. For simulation semivariogram model is invoked to simulate spectrum hole generation. Semivariogram is defined by the function

$$\acute{\gamma} = \frac{1}{2N(h)} \sum_{N(h)} \left(Z_i - Z_j\right)^2 \tag{6.2}$$

Where h is the assumed distance of separation; Z_i and Z_j are two points in the space and N(h) is number of points separating Z_i and Z_j.

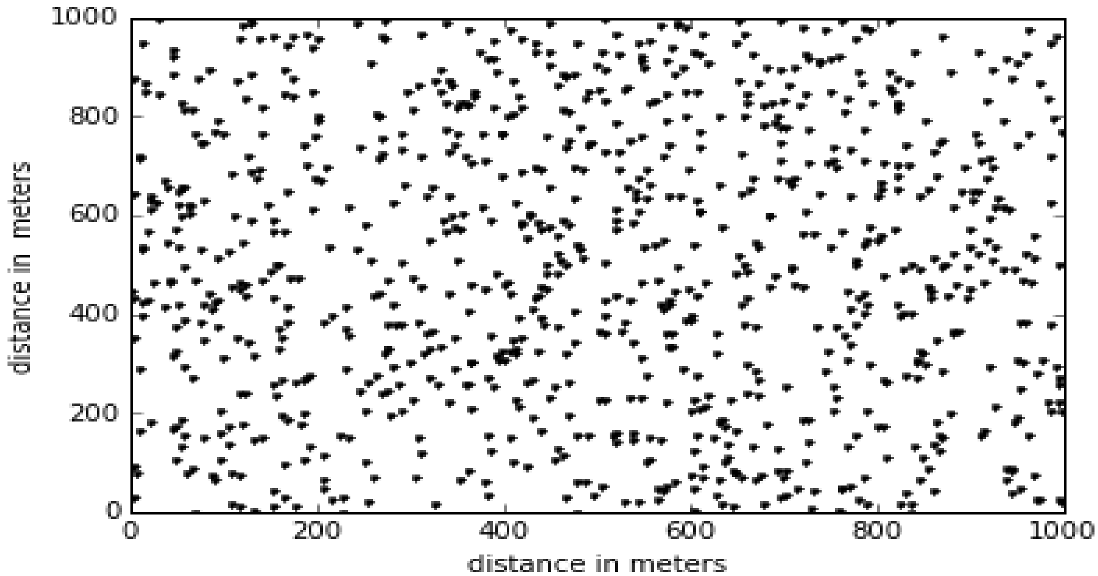


Figure 6-13 Distribution of Holes in Space, when Considering Semivariogram Distribution

Figure 6.13 shows the spatial distribution of spectrum hole. It is widely known that there are huge geographical regions where spectrum utilization is very low among some frequency at some time as well as most of the frequencies most of the time. In (Wellens, M, 2009) various semivariogram based correlation models are introduced. Many empirical results are derived for UMTS, WLAN and DVB-T wireless networks. These results can be applied to find out point where correlation becomes zero. This also marks "Spatial spectrum hole" for a frequency band. In this research, this detection technique is used to sweep space with frequency band of interest and check for zero correlation to flag spatial spectrum hole. Detection of the spatial macro spectrum hole must be performed with macro spectrum hole detector, which is a part of networked infrastructure.

6.5.4 Frequency spectrum hole detection

Frequency distribution is assumed to be Gaussian as given in (Wellens M, 2009) as shown in Figure 6.14. For the results of Figure 6.14, Gaussian distribution is assumed and with mean of 500 MHz and variation of 5 MHz.

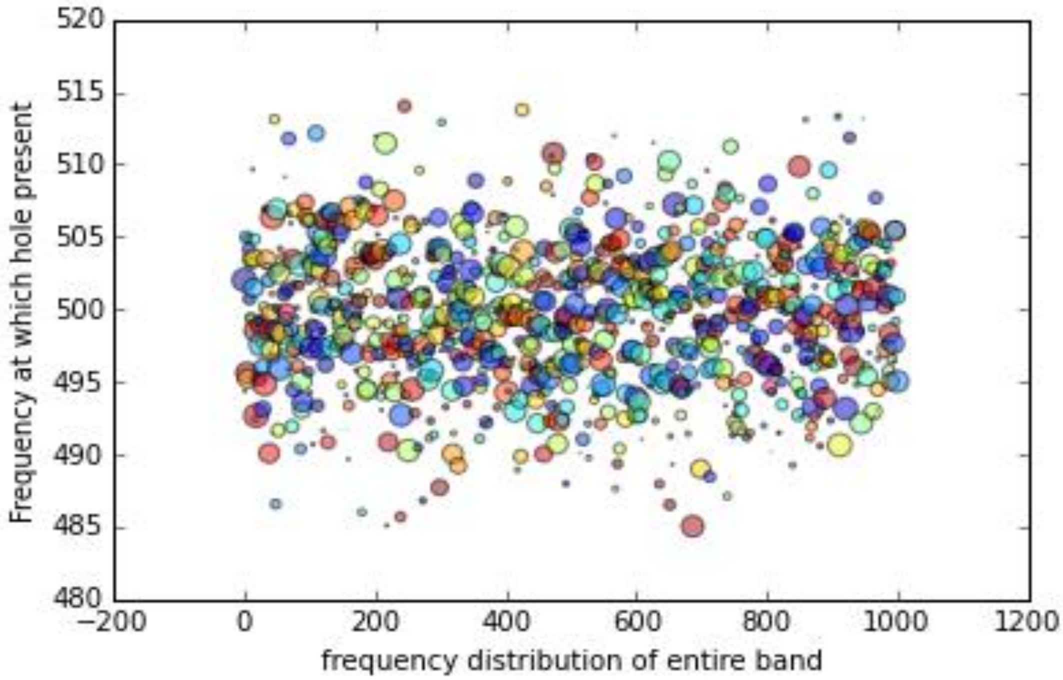


Figure 6-14 Frequency Holes Distribution Assuming Mean as 500 MHz and Variation of 5 MHz

Typical vacant spectrum with random bandwidth is shown in Figure 6.14. 3D SVM spectrum detector can be trained with this simulation setup.

6.6 Error in Detecting Spectrum Hole Using 3D Detector

Total error in detecting spectrum hole is union bound of errors in detection in all 3 domains. As analysed in (Hubbard and Raymond, 2003), the SVM error has two parts namely sampling error and regularization error. Also as stated by (Qiang Wu, 2004), the SVM error is given by generalization error. (Qiang Wu, 2004) analyses the details of SVM error in terms of loss function and the risk associated with loss function. (Qiang Wu, 2004) also suggests using relative loss function with respect to target function f. The error in misclassification of spectrum hole is misclassification error of SVM classifier after training. If X is the input data and Y is the classifier output, the misclassification error e(S) from SVM is defined by Equation (6.3).

$$e(s) = P[s(X) \neq Y] \tag{6.3}$$

Where s(x) is a misclassification error minimizer. Following (SVM Wikipedia, 2013), s(x) is written as:

$$s(x) = 2X1\{P(Y = 1|X = x) > \frac{1}{2}\} - 1 \tag{6.4}$$

However for simulations, python package sklearn and accuracy function are used to obtain estimate of error rate (error rate = 1 – accuracy). For different parameters of Gaussian, semivariogram and HMM duty cycle, confusion matrix is inserted to obtain error bounds of the SVM classifiers. Since the focus is on binary classification problem of detecting the spectrum hole, one can use confusion matrix to obtain:

- True position (t_p)
- False positive (f_p)
- True negative (t_n)
- False negative (f_n)

After many iterations or trials, the average values of these measures are obtained.
For each SVM classifier, the following can be defined:

$$\text{Probability of missed detection, Pm} = \frac{fn}{tn + fn} \tag{6.5}$$

$$\text{Probability of false alarm}, P_f = \frac{f_p}{t_p + f_p} \tag{6.6}$$

Assuming the total system probabilities are union bound of 3D detectors, which are independent of each other, system level missed detection probability is given by:

$$P_{msys} = (P_{md}) (P_{mt})(P_{mf}) \tag{6.7}$$

Where,

P_{md}: Probability of missed detection in space

P_{mt}: Probability of missed detection in time

P_{mf}: Probability of missed detection in frequency

System level false alarm probability is given by:

$$P_{fsys} = (P_{fd}) (P_{ft})(P_{ff}) \tag{6.8}$$

Where,

P_{fd}: Probability of false alarm in space

P_{ft}: Probability of false alarm in time

P_{ff}: Probability of false alarm in frequency

With these news metrics for measuring effective detection of spectrum holes, following heuristics for interference and spectrum efficiency of the overall network are obtained.

Interference to PU is directly result of missed detection and hence depends on Pmsys. It also depends on the speed of actions after detecting PU and therefore this is useful for switching time. In this research, interference to PU is correlated to accuracy of 3D SVM spectrum hole detector, considering detection is a continuous process after spectrum being occupied. Assuming that interference directly depends on probability of missed detection of PU, one can say.

$$I_{pu} = KP_{msys} \tag{6.9}$$

Where I_{pu} is the interference to PU and K is a proportionality function. This can also be written as:

$$I_{pu} = K(d,t,f)(\,(Pmd)(Pmt)(Pmf)) \tag{6.10}$$

$$I_{pu} = K(d,t,f)(\left(\frac{f_{nd}}{t_{nd}+f_{nd}}\right)\left(\frac{f_{nt}}{t_{nt}+f_{nt}}\right)\left(\frac{f_{nf}}{t_{nf}+f_{nf}}\right)) \tag{6.11}$$

Where K(d,t,f) is an interference proportionality function dependent on space, time and frequency. It can be further divided into components in space, time and frequency. But separability of the function into subcomponents may depend on model selected for this function, which is beyond scope of this thesis. It is assumed that K(d,t,f) is partially differentiable with respect to d, f and t. The function K(d,t,f) is also assumed to be completely separable in time, space and frequency. For a minimal interference to PU, the necessary condition is given by

$$\nabla I_{pu}(d,t,f) = 0 \tag{6.12}$$

Taking partial derivative of function I_{pu}in each domain,

$$\frac{\partial(I_{pu}(d,t,f))}{\partial d} = 0 \tag{6.13}$$

$$\frac{\partial(I_{pu}(d,t,f))}{\partial t} = 0 \tag{6.14}$$

$$\frac{\partial(I_{pu}(d,t,f))}{\partial f} = 0 \tag{6.15}$$

It is assumed that this partial derivatives yield extremum and all partial derivatives exist at a point (d0, t0, f0). So most optimal value for the resource block that minimizes the interference to PU is determined at (d0, t0, f0). Following this optimization technique, the infrastructure can assign the resource blocks to CR communication. Apart from this one can use multivariable stochastic gradient descent algorithm to find most optimal values of resource blocks to be assigned for CR communications.

Substituting the four probability components (tp, fp, tn, fn) in all 3 dimensions into Equation (6.7), the highest missed detection probability of the system that can be allowed is given by

$$Pmys = \left(\left(\frac{f_{nd0}}{t_{nd0} + f_{nd0}}\right)\left(\frac{f_{nt0}}{t_{nt0} + f_{nt0}}\right)\left(\frac{f_{nf0}}{t_{nf0} + f_{nf0}}\right)\right) \tag{6.16}$$

Corresponding to the resource block at (d0, t0, f0).

Apart from interference, there is a need to obtain the optimal throughput of CR network with Ipu = Ipu(Qspec) as a constraint.   Throughput of the CR network can be defined as:

$$T_{CR} = \frac{N(d,t,f)}{((P_{ft}) * (P_{fd}) * (P_{ff}))} \tag{6.17}$$

Where N (d,t,f) is the throughput proportionality function. Again it is assumed that N (d,t,f) is partially differentiable with respect to d, f and t.

$$T_{CR \to T_{CR}(optimal)} = \frac{N(d,t,f)}{((P_{ft}) * (P_{fd}) * (P_{ff}))} \Bigg| I_{pu} = I_{pu}(Qspec)$$

(6.18)

With constraints from Qspec as Ipu = Ipu(Qspec), the best throughput for CR can be obtained by assigning resource block at (d0, t0, f0). Throughput of CR at this point is given by:

$$T_{CR} = \frac{N(d_0, t_0, f_0)}{((P_{ft0}) * (P_{fd0}) * (P_{ff0}))} \tag{6.19}$$

Throughput of the CR network will be constrained by Qspec requirement of PU network. The specification of tolerable interference to PU will determine throughput achievement of the CR network. The scope of this thesis is on formulation of optimization problem and obtaining the bounds of throughputs of CR network as a function of probabilities of misclassifications. Further research studies can be carried out with respect to transmit power and interference reduction through better 3D classifiers.

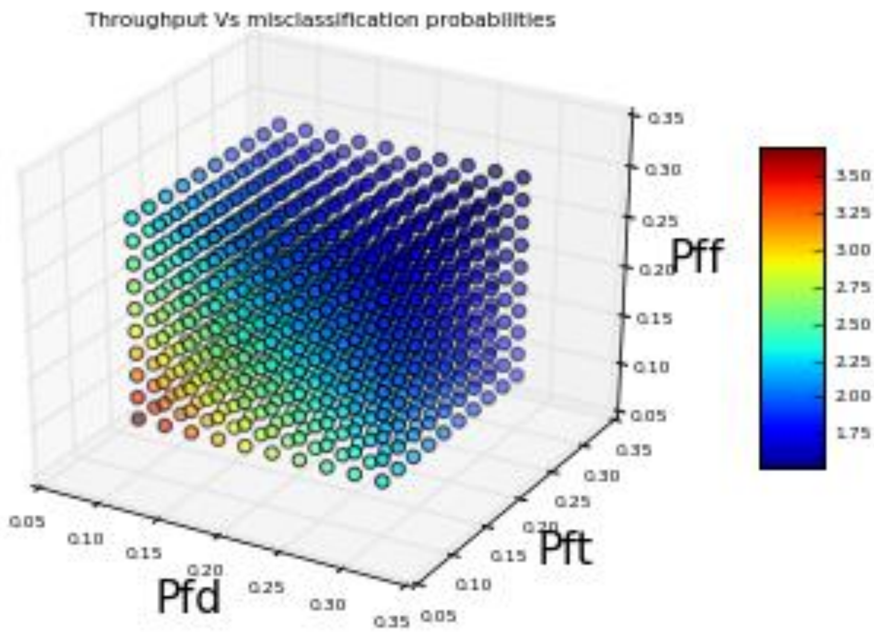


Figure 6-15 Throughput Mapped to 3D False Alarm Probabilities for a Given Qspec

Simulations parameters used in Figure 6.15 are probability of false alarm of what? in 3 dimensions. From the 3D false alarm map in Figure 6.15, one can constraint Qspec as limiting factor for the region of operation.

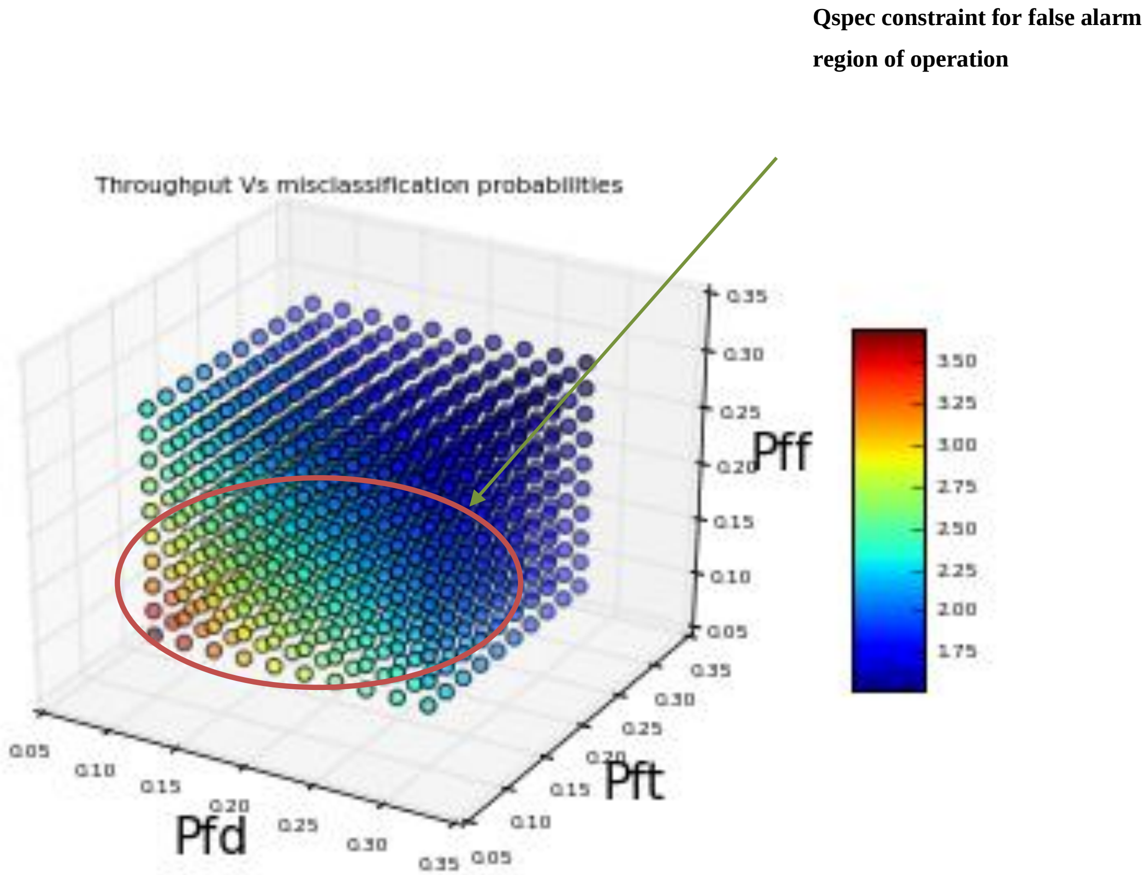


Figure 6-16 Qspec Constraint in the False Alarm Region of Operation

As seen from the results of Figure 6.15, throughput of almost doubles by reducing the false alarm probabilities in space, time and frequency. The throughput of CR based D2D networks can be enhanced by imposing the stiffer constraints on interference to PU and improving false alarm. As shown in the colour map of 3D simulation results of Figure 6.15, the throughput is maximum at lowest false alarm probabilities. It almost halves when false alarm probability is close to 0.3. Throughput of CR network is measured in bits/sec/Hz/unit area. Since 3-Dimensional resources are considered, frequency and area are accounted into the definition of spectral efficiency.

6.7 Algorithm for Spectrum Allocation Using 3D Spectrum Hole Detector

A block diagram of algorithm for the spectrum resource formation at the central infrastructure node is illustrated in Figure 6.17.

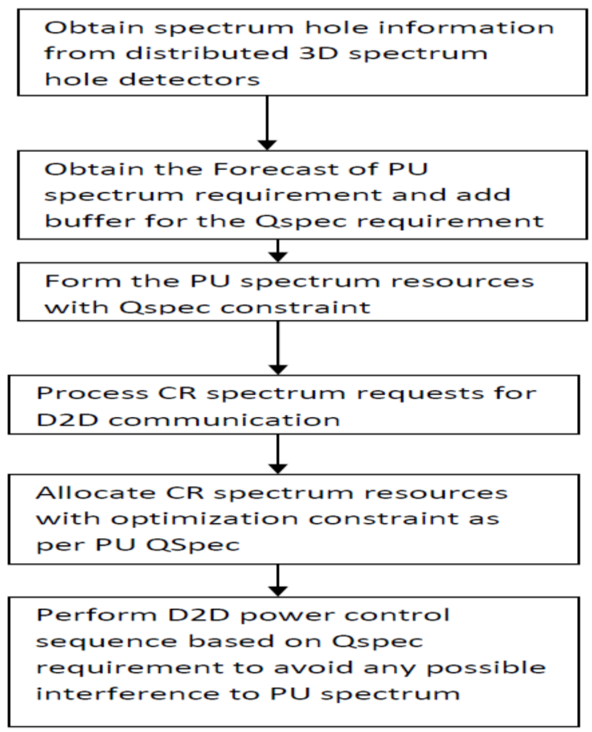


Figure 6-17 Algorithm for Qspec Optimization

Central part of algorithm is Quality of spectrum requirement for infrastructure network, which is defined as Qspec. Key innovation in this research is to dynamically know the required Quality specification (Qspec) of spectrum of PU. Once the quality requirement is known to both infrastructure monitoring the CR network and the CR nodes, the interference can be mitigated as discussed in the earlier sections. Therefore, the problem of minimizing interference to PU is problem of solving the classifier whose error probability or RoC characteristic satisfies the Qspec constraints.

6.8 Optimization of QSPEC

Typically, optimization problem in CR technologies is derived based on the time and probability of missed detection and probability of false alarm. This in turn leads to a need to determine the data rate of secondary user and protection to primary user. (R. Tundra, 2008) advocates metrics which are measurement of uncertainty and area recovered. However, it is difficult to compare different network topologies with these metrics. Absolute measurement of improvements obtained using CR is obtained in terms of bits/sec/Hz. This would provide the spectral efficiency improvements. When spectral efficiency is normalized with respect to the existing spectral efficiency of a network without CR and after deploying CR, one can sense the improvement in spectral efficiency. CR gain is defined as

$$\text{CRgain} = \frac{SpecEff_{CR+prim}}{SpecEff_{Prim}} \qquad (6.20)$$

$SpecEff_{CR+prim}$ is the spectral efficiency of network with CR deployment

$SpecEff_{\mathrm{Prim}}$ is the spectral efficiency without CR deployment

Thus the CR gain can be termed as a relative measure of the improvement in the spectral efficiency of the network in lieu of it being CR enabled.

CR technology is comprised of network topology, sensing technique and the protocol definition. Therefore to capture all these to prove merits of CR deployments, arising need is there to provide a metric to prove improvements in spectral efficiency. But since improvement in spectrum efficiency has to be constrained by quality of Spectrum usage by PU, CRgain is constrained with Qspec so that he optimization problem can be defined as:

$$CR_{gain} = \frac{SpecEff_{CR+prim}}{SpecEff_{Prim}} \{Q_{spec} = Q_{spec(opt)} \qquad (6.21)$$

Where, Qspec(opt) is the quality of interference free spectrum required by the PU. The Qspec(opt) depends on interference in spectrum of PU as well as interference from CR. Since it is extremely complex to provide usage elasticity in terms of PU spectrum interference from other PUs, the margin of that elasticity is left as it is and worst case PU channel is considered for the maximum PU interference and maximum possible CR interference to PU. Both are measured in terms of interference temperature given in (FCC Report ET Docket No. 02,135, Nov. 2002) and can be stated as:

$$IT_{ri} = P_{ij} - CI_{i,n} - NF_{ri} \qquad (6.22)$$

Where

IT_{ri} is interference temperature at the PU receiver

P_{ij} is the receiver power specification of the PU receiver

$CI_{i,n}$ is co-channel interference

NF_{ri} is the noise floor of the communication channel n is nth frequency band

n is nth frequency band

The contribution to interference temperature at the receiver of PU by CR is factored into co-channel interference $CI_{i,n.}$.

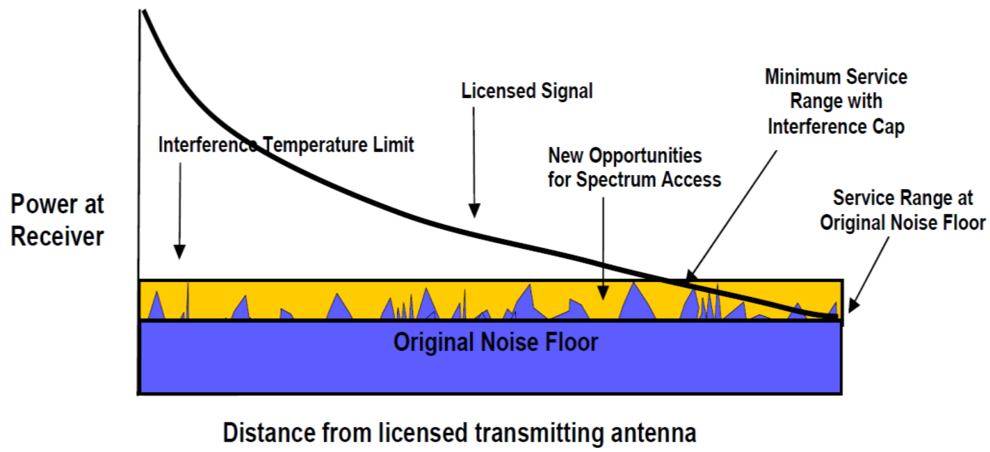


Figure 6-18 Interference Temperature (IT) Illustration (Courtesy: FCC-03-289A1, [53])

As stated in (FCC-03-289A1), which reinforces this research on distance-based resource allocation and 3-D spectrum sensing. As shown in chapter 5 of this thesis, the distance-based allocation increases the available bandwidth for overall communication by 50%. Considering that interference temperature is the limiting factor of Qspec, one can further conclude from the results of Figure 6.18, that the opportunity in the region between minimum service range with interference cap and the service range at original noise floor can be exploited significantly by reducing missed detection in CR systems.

The missed detection probability of the 3D-spectrum hole sensor is given in Equation (6.9). This is compared with missed detection probability of prior research described in Equations (3.5) and (3.6) which is normal distribution in single dimension (that is in frequency domain). The missed detection in 3D-spectrum hole detector is a combination of 3 variables and has 3 degrees of freedom, whereas in Equations (3.5) and (3.6) it is a single variable missed detection. Comparing these equations of 3D and 1D detection, it can be concluded that 3D Spectrum hole sensor exhibits lower missed detection.

With an assumption that all the 3 degrees of freedom to be Gaussian, ratio of missed detection of 3D and 1D missed detection is given by:

$$md_r = \frac{Pmd_{3D}}{Pmd_{1D}} \tag{6.23}$$

Where,

md_r is the missed detection probability improvement of 3D over 1D spectrum hole detector

Pmd_{3D} is the probability mass function of missed detection of 3D detector

Pmd_{1D} is the probability mass function of missed detection of 1D detector

Assuming Gaussian distribution with 0.1 mean, one gets:

$$E\,[\,md_r] = \frac{\text{pmf}*\text{pmt}*\text{pmd}}{pm} = 0.01 \tag{6.24}$$

$E\,[\,md_r]$ is expectation of missed detection

One can expect missed detection probability obtained through proposed 3D detector to improve by a factor of 100 over that obtained through 1D spectrum hole detector. In CR, interference is proportional to the missed detection and therefore Qspec. Therefore the anticipated improvement in the expected noise floor in 3D spectrum hole detector compared to 1D spectrum hole detector can be by a factor of 100.

6.9 Summary

This chapter has presented the concept of 3-Dimensional spectrum sensing instead of a conventional 1-D spectrum sensing. The proposed 3-D spectrum hole detection considers time and space in addition to frequency domain. This will provide significant flexibility in allocating resources in an overlaid network. The structure of resource blocks with 3 dimensional factors will result in optimal Q_{spec} compared to 2-D or 1-D detection. With resource map available to infrastructure-based network, allocation of resources to CR communication is better with 3-D structures than compared to 1-D or 2-D structures. This chapter has also presented a generic setup for 2-level spectrum hole detection using macro and dynamic spectrum hole detection. The same model is applied to all the 3 domains of 3D spectrum hole detector. Support Vector Machine (SVM) with 3D RBF kernel is used to estimate the spectrum holes. 3D RBF is used to transform the data samples collected from domain comprising space, time and frequency and then to convert it to feature space. This chapter has presented the system level probability of missed detection and probability of false alarm applicable for 3D spectrum sensing. The missed detection in 3D-spectrum hole detector is a combination of 3 variables and has 3 degrees of freedom. In contrast with a 1D- spectrum sensing, probability of missed detection is with a single variable. Comparing the derived equations with 3D and 1D detection, it is concluded that 3D spectrum hole sensor exhibits lower missed detection. It is shown that the adaptation of 3D spectrum hole detection leads to decreased probability of missed detection by a factor of 100. The resulted decrease in the probability of missed detection of PU directly translates to reduction in interference temperature at PU. Because of this, there is an additional margin in new spectrum opportunity part. In this chapter it is proved that by assuming the proportionality constant for interference temperature and missed detection to be logarithmic function, total usable bandwidth of CR network can be increased by a factor of 2 resulting in a 2-fold improvement in spectral efficiency of the network. This is the key result using the 3D spectrum detector in place of 1D or 2D spectrum detector. As a figure of merit in the assessment of improvement in the spectral efficiency because of CR enabled network, a term called CR gain is proposed. CR gain is defined as the ratio of Spectral efficiency of the network with the deployment of CR to the spectral efficiency of network without CR. Thus the CR gain can be termed as a relative measure of the improvement in the spectral efficiency of the network in lieu of it being CR enabled.

A summary of performance comparison of 1D spectrum sensing and 3DSS techniques is presented in Table 6.2. 3DSS which has the domains of Time, Frequency and Space outperforms the 1D spectrum sensing in the four performance metrics as shown in the results of Table 6.2. The achievable usable bandwidth with 3DSS is 3 times higher than that realisable with 1D spectral sensing technique. 3DSS provides improved reliability in terms lower false alarm and missed detection. It also significantly reduces the IT of the system. As shown in Equation (6.22), noise floor decreases with reduction in IT. Reduction in IT translates to enhancement of spectral efficiency.

Table 6.2 Key Performance Comparison Between 1D Spectrum Sensing and 3DSS

Performance metrics	**1D spectrum sensing**	**3DSS in time, frequency and space**
Usable bandwidth for CR	150 MHz	500 MHz
Range of Probability of false alarm at fusion centre	0.1 to 0.01	0.01 to 0.0001
Range of Probability of missed detection at fusion centre	0.1 to 0.01	0.01 to 0.0001
Interference Temperature (IT) (dB kelvin/Hz)	>150	< 100

Chapter 7 - CR System Model for MANET Overlaid on the Heterogeneous Networks

This chapter deals with a simulation model for overlaying of CRMANET on a heterogeneous network. The chapter also discusses the significant additional details required in updating route table of CRMANET when overlaid on a heterogeneous network. A novel 3DSS Routing algorithm used for 3D spectrum sensing based CRMANET is also proposed in this chapter. A discussion on the implementation of DSDV protocol on MANET overlaid on heterogeneous network is also presented in this chapter. A novel method of routing protocol which is termed as 3-Dimensional Spectrum Sensing (3DSS) routing protocol is proposed in this chapter. It also highlights the importance of a scheme for updating the 3DSS route table and the application of SGD algorithm for the optimization in updating the route table. This chapter concludes that with an overlay of CRMANET on heterogeneous network and deployment of 3DSS routing, total spectrum efficiency improvement is 230% relative to that with CRMANET.

7.1 Introduction

The MANET communication once bootstrapped on the infrastructure network, must perform its own signaling and control after initialization. As shown in the Figure 7.1, the CRMANET once setup, will follow the signaling of its own. It also performs the distributed routing and link maintenance algorithms. All the CRMANET nodes also perform the functions of MANET. In addition to all MANET functions, the CRMANET nodes also perform spectrum sensing and receives frequency assignment from the infrastructure. As shown in Figure 7.1, the CRMANET is overlaid on the infrastructure based heterogeneous network. CRMANET is used for single hop D2D communication.

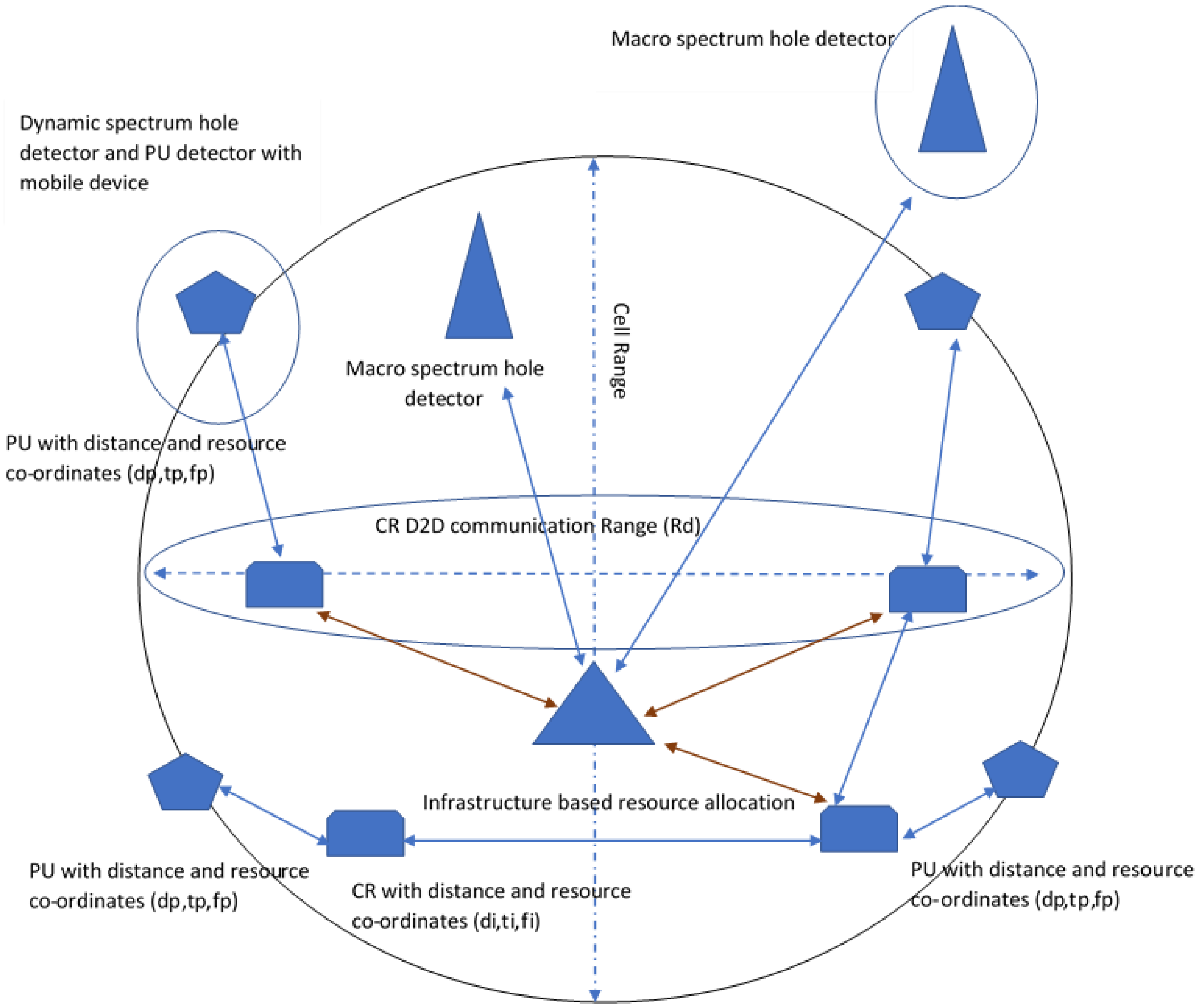


Figure 7-1 MANET Overlay on the Heterogeneous Network

Multihop is achieved using the relay of the many single hop links. All resources are defined by triplet (d, t, f), with resource allocator assigning the triplet with priority to PU. CRMANET contains two channels, spectrum hole sensing channel and the D2D CR communication channel. The resource allocation map shown in Figure 7.2 will be used to route the CR D2D communication.

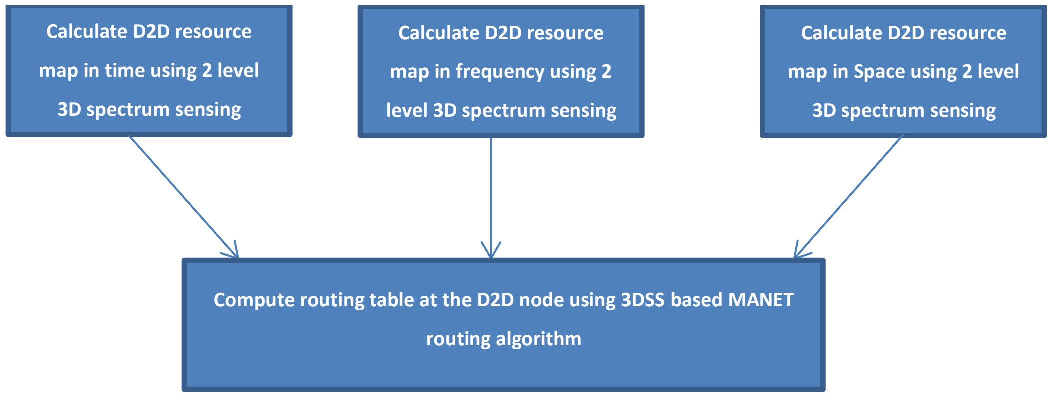


Figure 7-2 3DSS Initial Setup

Further fusion centre in Figure 7.1 acts as the resource monitor and allocator. The CRMANET receives resource map updated from the fusion centre, which helps in determining optimal communication and resources for sensing. The allocation of resources for sensing involves allocating frequency of sensing according to the estimated distance of PU from the fusion centre. The model for same device being used for D2D communication and the cellular communication provides total spectral efficiency improvement at the device. Overlaying CRMANET on the heterogeneous network like 4G/5G networks offers flexible usage of both CR and licensed spectrum. Recent 5G standards (5G mobile standards, 2011) also have a provision for switching the PU into unlicensed band (2. 5 GHz and 5 GHz).

7.2 A 3-DSS Routing algorithm used for 3D spectrum sensing based CRMANET

CRMANET requires special routing algorithm to support CR functions. Since the routing involves sensing and switch to newer resources, the routing algorithm must incorporate the same. Apart from regular link based or destination-based routing, 3DSS based routing must be incorporated. In 3DSS, the routing table incorporates CR functions. The 3DSS routing table can be centrally calculated initially by infrastructure based base station. As shown in Figure 7.2, the routing table is populated with the help of overlay on heterogeneous network. D2D resource mapping is calculated using the 2-level spectrum sensing based on 3D spectrum hole detection and macro estimation of spectrum hole at network level. The (d, t, f) triplet is converted to source and destination nodes as shown in Table 7.1.

Table 7.1 indicated routing table for source node 1, according to topology of network given in Figure 7.4. SeqNo in the table is generated by destination node. Each of the sequence number is even if link is present, else it is odd. Topology of nodes is given in Figure 7.4. Topology contains 15 nodes. The routing table for node 1 is given in Table 7.1. Similarly routing table for different nodes can be configured with dest , next node, distance to next and sequence number.

Table 7.1 Typical Routing Table for Source Node 1

Dest	Next Node	Dist (meters)	SeqNo
2	2	1	22
3	2	2	26
4	5	2	32
5	5	1	134
6	6	1	144
7	2	3	162
8	5	3	170
9	2	4	186
10	6	2	142
11	6	3	176
12	5	3	190
13	5	4	198
14	6	3	214
15	5	4	256

As shown in Figure 7.3, there are two types of links in CRMANET nodes namely D2D data link and infra based configuration link. Configuration link represents network overlay, by means of configuration from heterogeneous network to D2D network. CRMANET themselves will have no capability to assimilate information about wide resource maps. As indicated in Chapter 2, there are limitation of local optimization in using gradient descent algorithm to determine the spectrum hole using CRMANET. By converging to sub optimal resources, standalone CRMANET does not provide good improvements in spectrum efficiency improvements.

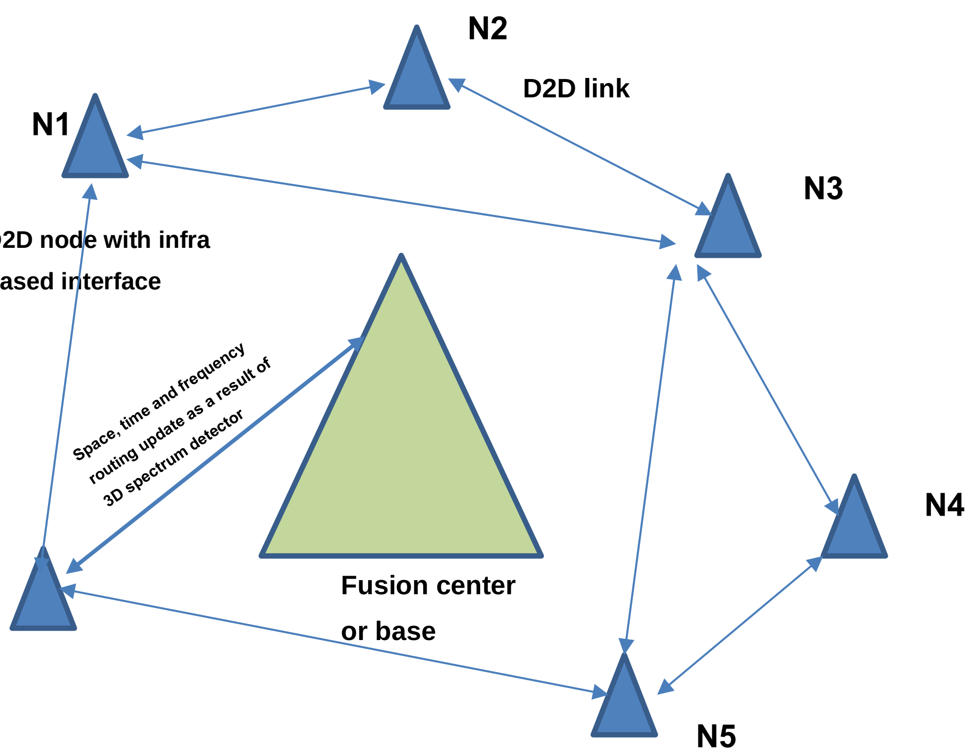


Figure 7-3 CRMANET Resource Information Received from the Base Station of Infrastructure Based Network

As a resulting consequence of very high missed detection probabilities, there can be an increase overall interference temperature leading to reduced opportunity to exploit unused spectrum. On the other hand, using the resource mapping obtained from 3DSS provided by the infrastructure network, will result in optimal usage of spectrum resources in CRMANET and this also reduces the missed detection probability as discussed in chapter 6. Another improvement in CRMANET is the potential to develop various routing algorithms based on the 3DSS detection algorithm. Various routing protocols can be implemented using 3DSS detection and 3D resource structure. Some of the possibilities covered in this research are table-driven routing, on-demand routing and hybrid routing protocols. In table driven routing, each CR node maintains its own table of information about network topology. Unlike normal MANET without overlay, the information is updated by heterogeneous network. Main drawback of the table-driven routing in MANET is periodic exchange of the information among the network nodes. This information exchange generally floods the entire network. This consumes higher bandwidth than on-demand routing protocols. The nature of CR communication requires frequent exchange of the topology information, which aggravates the problem of the MANET routing protocols, if the D2D or MANET communication is not overlaid for controls on the heterogeneous infrastructure-based network. As shown in Figure 7.3, the fusion centre will update the setup information through broadcast of resources to be used in table information. Since update is broadcast to all the nodes, broadcast channel defined according to structure (d, t, f) uses minimal resources and has more flexibility to use least required resources by CRMANET and primary network.

Apart from the table-based routing, on demand routing can be implemented with 3DSS based CRMANET. On demand routing is a reactive routing protocol. In this type of routing protocol, the connections are established as per usage and network topology. The network connection is established when required. This type of protocol does not exchange the routing information periodically. D2D communication with same device being both primary and CR user can use on demand routing, which saves the flooding of the

CRMANET network. However, the disadvantages of the on-demand protocol are that connection setup time before initial communication between nodes can introduce latency in the network. Therefore, on demand routing may not be `suitable for latency sensitive network. Another shortcoming of on demand routing protocol for CRMANET and D2D application is, the sensing and switching time of PU increases due to network, which can increase the interference to PU and hence larger contribution to interference temperature.

Hybrid scheme of routing protocols can be deployed in CRMANET overlaid on the heterogeneous network. In this type of routing, when the distance of PU is estimated at a distance, the table-based routing is used within that distance. Beyond the estimated distance vector, on demand routing is used. This hybrid scheme uses bandwidth efficiently and does not flood network with very frequent exchange of routing information.

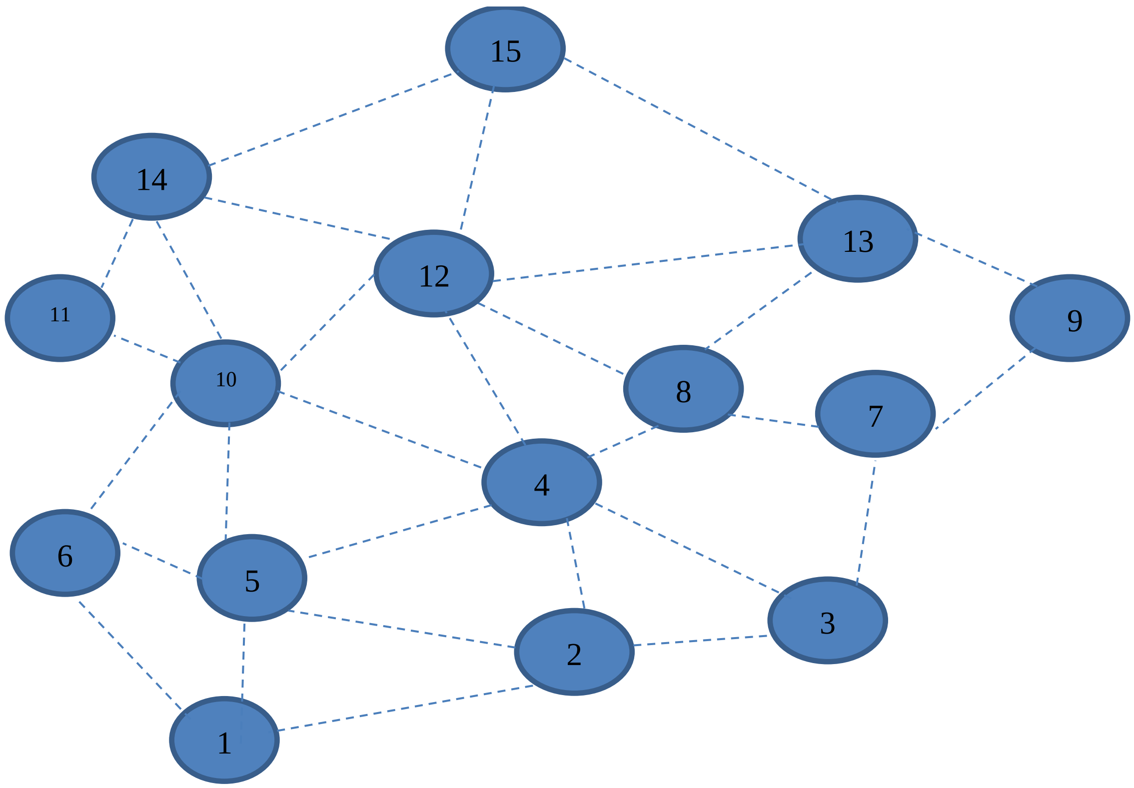


Figure 7-4 Network Topology for Table Based MANET Routing Algorithm

Typical MANET node is WIFI enabled node with maximum of 4 active channels on the RF interface. MANET node here is assumed to be working in a 2.5 GHz band.

Figure 7.4 shows the simple MANET. This is a 15 node MANET with bidirectional link. Maximum number of neighbouring nodes for any given node is 6. The MANET follows the table-based routing algorithm given in Table 7.1. This is a type of table-based routing algorithm called Destination Sequenced Distance-Vector (DSDV) routing algorithm proposed in (C. Siva Ram, 2004). This is one of the early routing algorithms to be used in MANET. It is an enhanced version of distributed Bellman-ford algorithm where each MANET nodes maintains its own table that provides information of shortest distance and the first node on the shortest path to every other node in the network. It uses the sequence number to avoid the loops in the route calculation and avoid count to infinity problem. Lookup table provides the routes to all destinations from the node which maintains the table quickly. Most serious issue of this protocol is that table must be exchanged between neighbours to maintain up-to-date status of the network. This not only require extra bandwidth for exchanging the table updates, but it suffers from the hidden node problem. Table can be updated with incremental dump or full updates of the table. Incremental updates are used when destination node or updater sees no momentous change in network topology. If network topology changes significantly, then network will be flooded with full dump to all nodes. This leads to increase in signalling bandwidth and reduces the communication bandwidth. Incremental updates lead to lesser control overheads, but a broken link or addition and deletion of nodes leads to heavy control overheads with possibility of flooding the network. Table updates are initialized by the destination node, where current node is connected. The sequence number used for the update initialized by the destination node is always greater than the current sequence numbers in the table. For incremental route table update when a few nodes are updated, there is a 20-30% overhead for control and signalling update in a MANET (C. Siva Ram Murthy, 2004). But scenario of flooding where every node receives the table update may render complete jamming of the network and no communication will be possible between the nodes.

Figure 7.5 shows route table update in DSDV based routing algorithm. Figure 7.4 assumes only data communication on MANET, where link is established. Figure 7.5 shows link establishment via dotted lines. When link is getting established, there will be no data communication possible because of low bandwidth channels deployed in MANET. There is up to 50% of time and bandwidth requirement for link establishment and hence no communication possible during link establishment as shown in Figure 7.5.

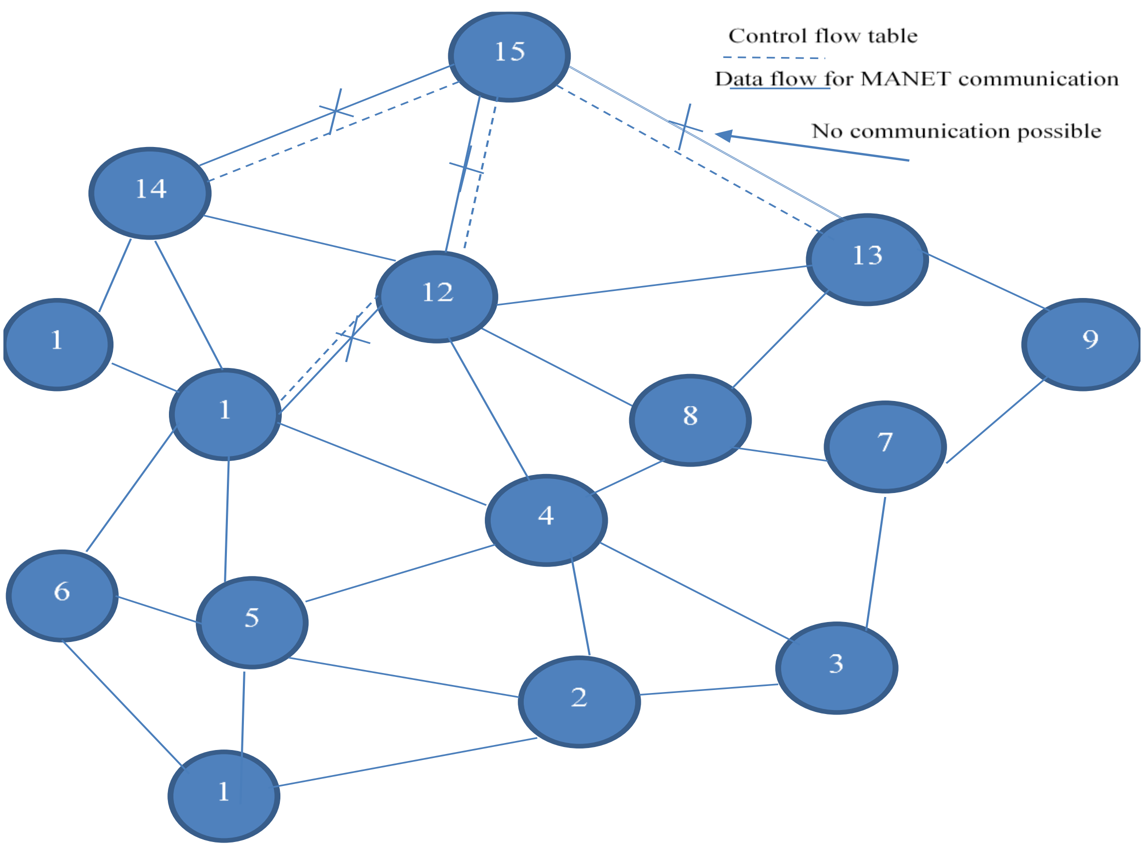


Figure 7-5 Bandwidth Usage in Incremental Update Using DSDV Table Based Routing Algorithm

The loss of communication link in CRMANET is more common than MANET due to frequent switching of spectrum. If DSDV routing is used as it is defined in this section, most of the time network would be in the state of outage. This is true for shared link for data communication and signalling architecture. Most MANETs would require low power implementation of the transceivers and hence provides shared signalling and communication channel. Also in normal cases of stable network this provides higher network bandwidth, since signalling is used only 10% of the time (C. Siva Ram Murthy, 2004) But if network becomes unstable or it must update the table more frequently, then easily it may degrade the network bandwidth and spectral efficiency. Best case scenario is to have dedicated channel for signalling and communication. In this case effective bandwidth of the network is reduced by 50%. Considering Equation (3.11) since available bandwidth reduces by 50%, the total effective spectrum efficiency of the CRMANET with DSDV routing protocol reduces by 50%, even with usage of the bandwidth of PU, when unused. It can be lower than 50%, when one considers the interference to PU due to hidden node problem and convergence to local optimum when using GD algorithm discussed in chapter 2.

Figure 7.6 shows the case of flooding of MANET networks due to poor wireless channel. When the wireless channel conditions deteriorate, MANET nodes try to renegotiate link. This leads to flooding of communication channel with many repeated attempts of link negotiations. This will lead to condition where little or node communication is possible. This condition is called flooding. Flooding is one of the drawbacks of MANET.

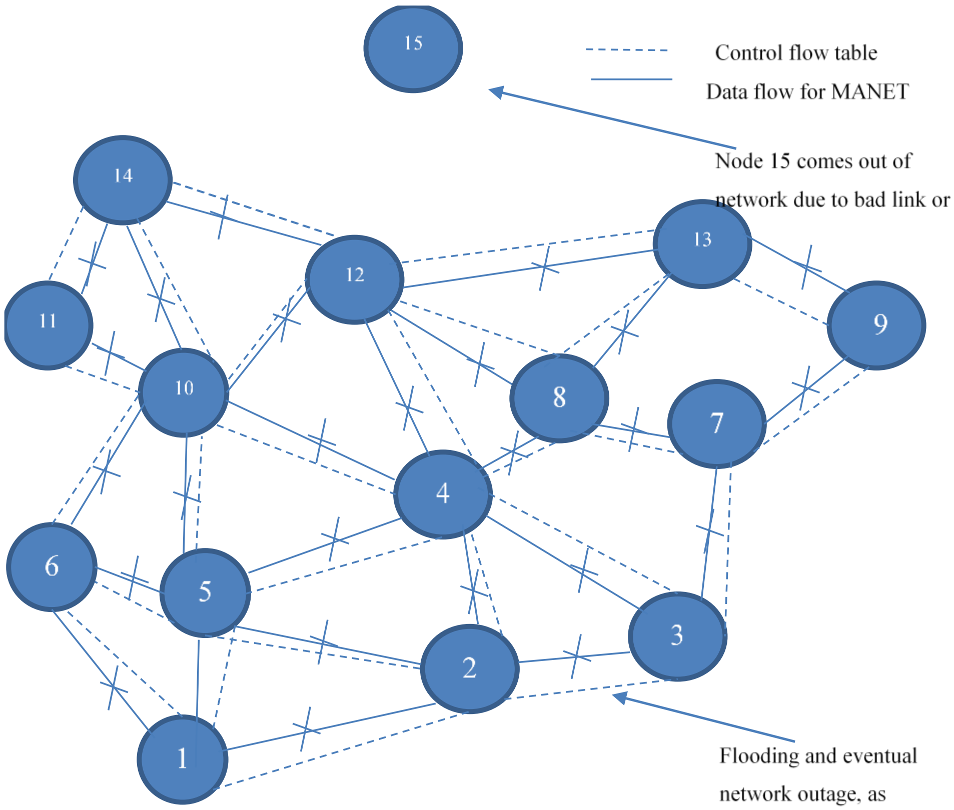


Figure 7-6 Flooding in the DSDV Based MANET and Resulting Network Outage

7.3 DSDV as Implemented on MANET Overlaid on Heterogeneous Network

To overcome the drawback of flooding and hidden nodes, this research proposes overlaying MANET control on the heterogeneous network. Overlaying the CRMANET on heterogeneous network requires infrastructure since the nodes provide the control information to all participating nodes. Definition of MANET is that nodes are Adhoc and does not require infrastructure. But using hybrid approaches as listed in chapter 2, provides better spectrum efficiency. Also broadcast channel can be used with bigger size of table to save bandwidth of the network. There is always a trade-off between the update payload and frequency of the update. Considering smaller payload of table of one node, update must be performed at higher frequency. Assuming update carries all the tables of the network, update can be done in lower frequency.

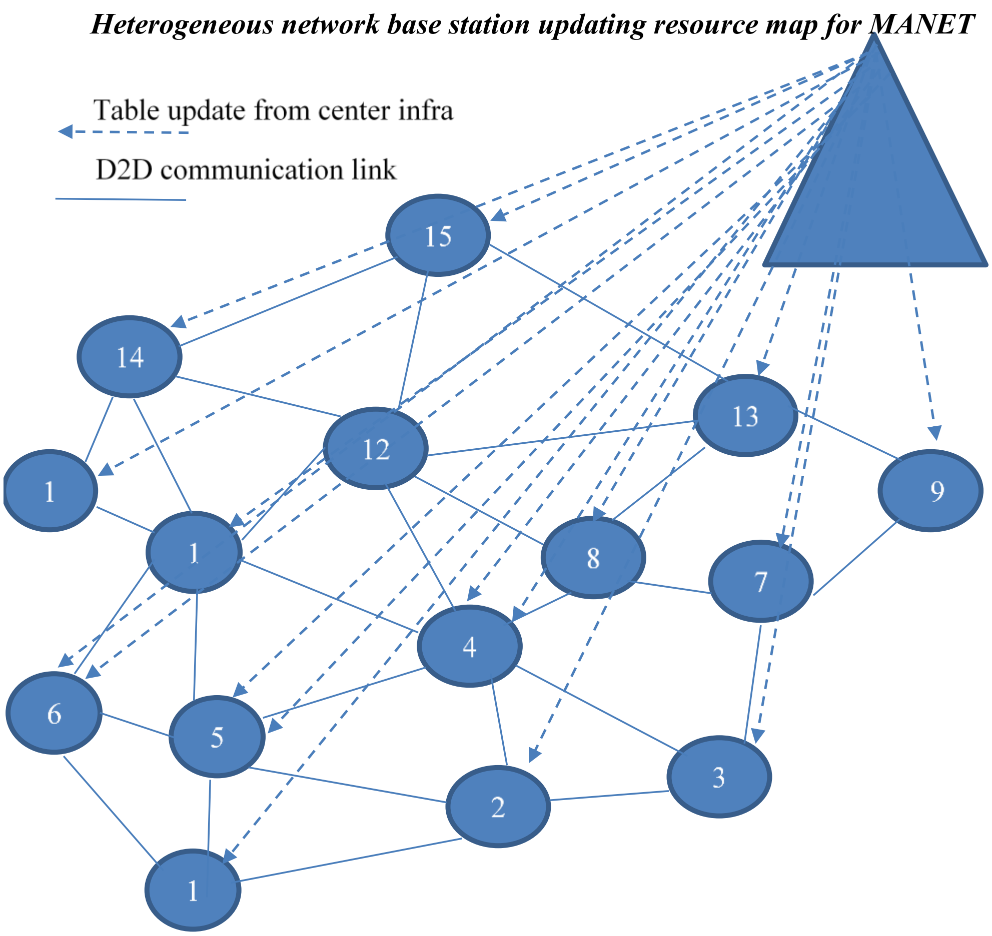


Figure 7-7 MANET Overlay for Control Information from Heterogeneous Network

As shown in Figure 7.7, the broadcast channel is used to update the table of each node. In this scheme, all the nodes in MANET listen to single channel for link update given by the central base station (and fusion centre). Difference between Figure 7.6 and Figure 7.7 is that base station provides the link establishment on one of more broadcast channels. But in Figure 7.6 there is no provision for such infrastructure-based overlay. Therefore, this leads to inefficient bandwidth and time usage for link establishment. This limitation is overcome through the solution proposed in Figure 7.7 by having broadcast channel to help in the establishment of the link. There are many ways to architect the update payload of broadcast channel. Two schemes for updating the payload of broadcast channel are considered in this thesis.

7.3.1 Node Number Based Round Robin Update

In node number based round robin update, the update payload contains the header as node number and payload as one entry of node table. Same table is sent on a broadcast channel. Depending on the node number, one of the CRMANET nodes decodes the same. Disadvantage of this method is security of the CR node is compromised by broadcasting to all other nodes. This can be overcome by including the public key encryption and only the node which is the owner of the table will be able to encrypt the same. Resulting frame structure are shown in Figure 7.8.

CR Node number and Public key (512 bits)	CR node Routing table for 20 node fully connected network (1 Mb)

Figure 7-8 Frame Structure for Routing Table Update from Broadcast Channel

Considering update interval of 500 microseconds with 1 MHz carrier, the heterogeneous base station can update 20000 CRMANET nodes per second. However, considering switching and sensing time constraints of the CR to be around 20 ms, base station can update tables of 40 CRMANET nodes. 20 ms framing is a standard framing structure proposed in LTE. Further LTE also provisions smaller frames of 5 ms (3GPP, 2015). In this thesis a framing of 20ms is considered.

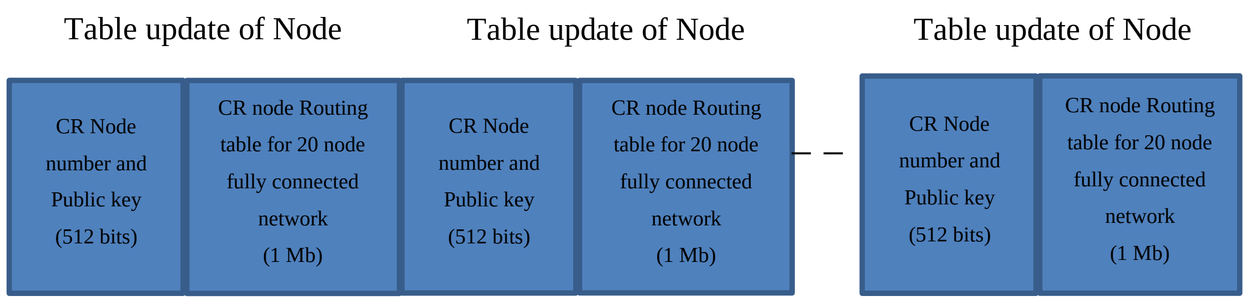


Figure 7-9 Multi Frame Update Structure of the Routing Table with Duration of 20ms

As shown in Figure 7.9, for each CRMANET network multi frame structure of 20 ms duration can be used to update all the nodes. Since it is time division multiplexed broadcast channel, the amount of bandwidth allocated for table update is considerably lesser compared to DSDV protocol-based table updates. Assuming 100 MHz of total network bandwidth of the DSDV based CRMANET, considering 50% utilization, 50 MHz is used for data communication (C. Siva Ram Murthy, 2004). Considering overlay over heterogeneous network and 20 ms multiframe update of the tables, 2 MHz bandwidth is used out of 100 MHz network bandwidth. This results in the saving of 48 MHz in the bandwidth of CRMANET. The limitation of this method is 20 ms multiframe structure, which imposes limitation on switching time of CR node. In cases of faster CRMANET networks with higher mobility and requirement for faster switching time, this method cannot be used.

7.3.2 OFDM Shared Symbol for Table Update

As described in the chapter 2, OFDM downlink channel can have shared symbols. This will be very efficient for broadcast channels.

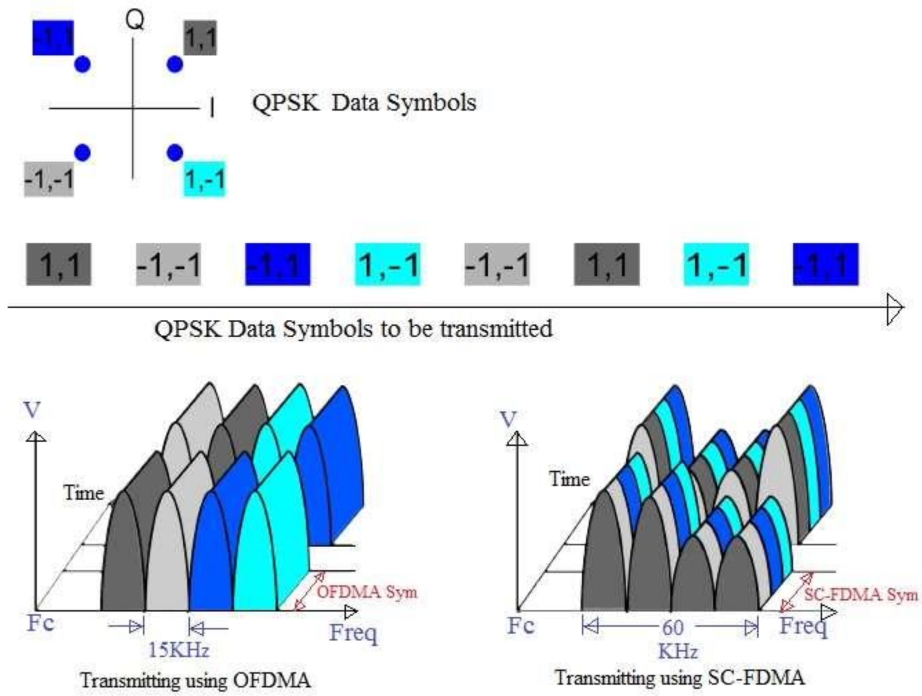


Figure 7-10 OFDM Shared Symbol for CRMANET Node Table Updates

Figure 7.10 shows OFDM symbols and modulation schemes in LTE. Downlink channel is supported by single OFDM shared symbol across channels and uplink is supported by SC-FDMA with multiple and heterogeneous symbol structure to support different transmit bandwidth by individual nodes. Both CR node and PU can have shared symbols on downlink and different transmit frequencies in uplink.

Unlike time division based round robin scheme of updating nodes in first option, in this option, the shared symbol is used. Symbol duration is 5 ms and frequency channel width is 15 KHz (Reference). Advantage of this method is that it can greatly reduce the channel interference with OFDM and time for update is 5 ms, which is symbol width of shared symbol. This will reduce the switching time of the CRMANET nodes. Disadvantage of this method of update is that it requires OFDM transceiver. For some MANET applications like sensor networks, this is very prohibitive because of high power requirements of OFDM transceiver. However, when the same device acts as both PU and CR node, OFDM air interfaces can be reused for both cellular communication as well as D2D communication.

From detailed description of the above two methods of table update, it can be concluded that each method has its limitations. If the D2D communication is used for low power sensor network, first method of Time Division multiplexing with multi frame structure can be used. If faster network implementation of OFDM on Wi-Fi, ZigBee and Bluetooth are used, the method of shared OFDM symbol can be used. Further OFDM based networks require much less synchronization compared to CDMA based networks. But the significant power consumption in modulation/demodulation appears to be prohibitive for low power sensor network.

Use of simple time division multiplexer modulation scheme such as GSM based 2G air interface will be good enough for low power sensor networks. Recently 3GPP launched low power LTE, which can be used in medium power applications (3GPP,2015). LTE direct would be an ideal choice for mobile devices like mobile phones, tablets and laptops which implement the CRMANET and can be connected to heterogeneous networks. Further the heterogeneous network base station will be updating many nodes of CRMANET in an optimal way according to the detection of the presence of PU and geographical information of the sub networks. Figure 7.11 shows hierarchical network management of overlay to obtain optimal usage of resources. There is a common base station of fusion centre and there are second level hierarchical fusion centres, which have different interfaces. The second level fusion centres have a common interface to base station, but different interfaces to MANET networks. For example, one second level fusion centre can work WIFI direct and other can work with D2D of LTE. Each of these second level networks can support different frequency bands, algorithm to update table and several types of MANET topologies.

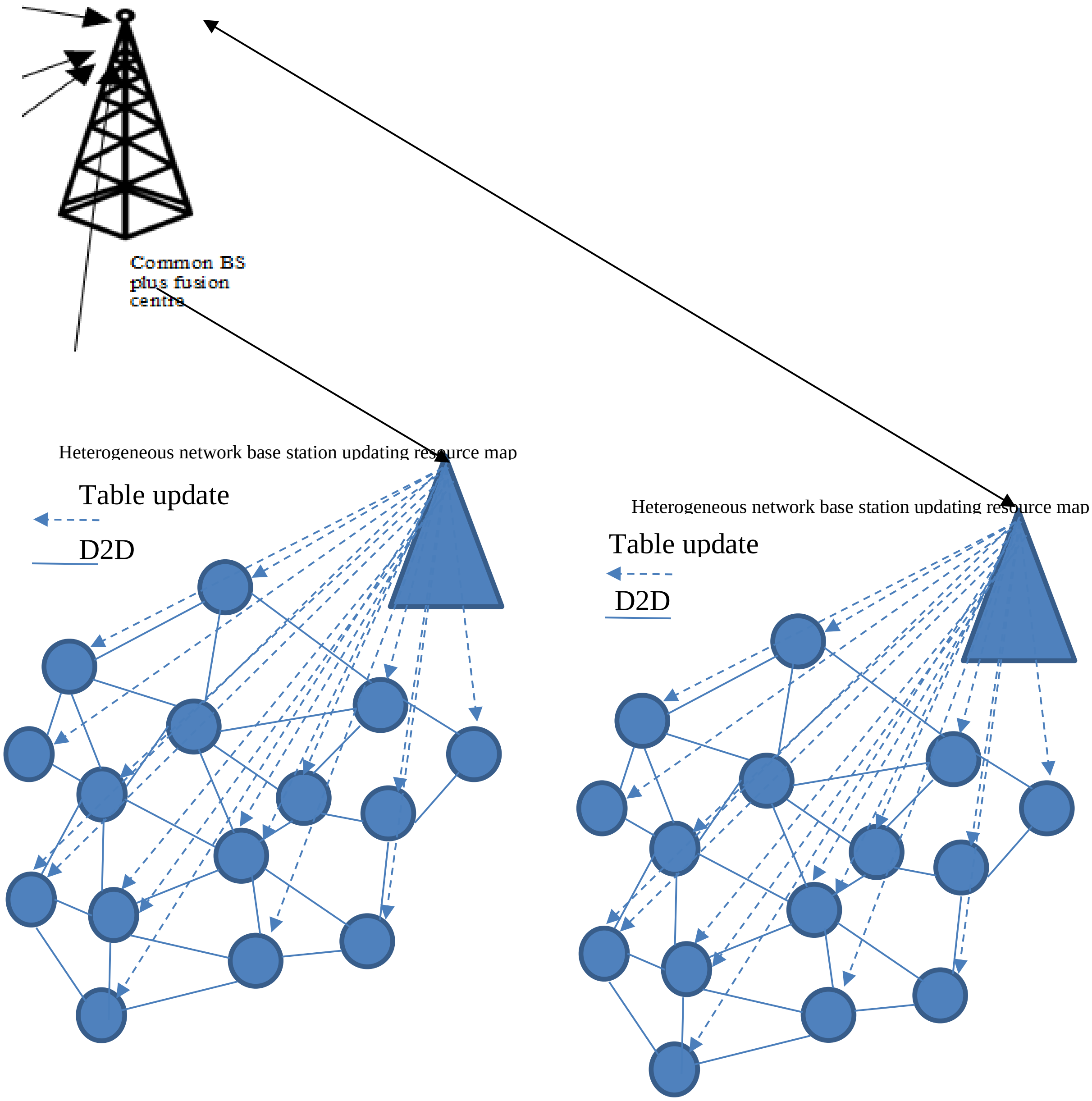


Figure 7-11 Hierarchical Heterogeneous Network with D2D CRMANET Subnets

7.4 3D SS Routing Table

Section 7.3 suggests various issues with MANET and difficulties or challenges in the deployment of CRMANET. Routing algorithm must account for all 3 dimensions of time, frequency and space to overcome these issues. Hence there is an acute need for a newer routing protocol to accommodate spectrum agility. This thesis provides novel method of routing protocol which is termed as 3-Dimensional Spectrum Sensing (3DSS) routing protocol.

Table 7.2 3DSS Routing Table Used for Next node calculation for Spectrum Sensing and Communication Functions

Destination Node ID	Number of hops	Next Node	D2D Routing Frequency resource (in MHz)	D2D Routing Time resource (in millisecond)	D2D Distance from the current node (in meters)	Sequence number
1	1	6	700	600	50	6
2	3	6	1800	888	10	12
3	1	4	700	10000	1000	14
4	2	1	722	8888	133	246
5	1	3	1810	9000	333	1024
6	3	3	700	78	100	3000

Comparing the format of Table 7.1 of DSDV routing protocol with Table 7.2 of 3DSS routing protocol, two differences can be seen. These are the addition of 3D D2D resources in the routing table of Table 7.2 as well as inclusion of (d, t, f) triplet to decide on routing is extremely important for spectrally agile technology like CR.

The size of the routing table size is around 64000 entries based on combination of number of frequencies, time and spatial resources available for routing. **S**ome of the entries may be dropped or invalid due to unavailable frequency or distance or time slot. Valid routes are populated by the network infrastructure, where MANET is overlaid. Invalid routes are dynamically configured and need to be taken care in link maintenance algorithm. During the time of initialization, "Route ranks" are given by infrastructure. Considering same route table as given by Table 7.1 with DSDV based network shown in Figure 7.6, the update table for modified DSDV incorporating 3DSS is shown in Table 7.3.

Table 7.3 Modified DSDV Table after Applying 3DSS Routing for Source Node 1

Dest	Next Node	Frequency resource (f) in MHz	Time resource (t) in millisecond	Space resource (d) in meters	SeqNo
2	2	700	100	1	22
3	2	1500	1000	2	26
4	5	2500	4000	2	32
5	5	779	40	1	134
6	6	789	4000	1	144
7	2	803	500000	3	162
8	5	789	45194	3	170
9	2	779	8900000	4	186
10	6	1500	340000	2	142
11	6	700	780000	3	176
12	5	730	7489491	3	190
13	5	792	848575932	4	198
14	6	878	4890212	3	214
15	5	2340	455	4	256

As shown in Table 7.3, main addition in 3DSS routing table is the inclusion of frequency and time resources. DSDV contains only distance resources for routing. However, calculating distance resource to populate the Table 7.3 is according to distance vector explained in Chapter 5. Time domain part of spectrum resource is allocated according to the estimated time a frequency band is expected as calculated by 3DSS algorithm using SVM in time domain**.** Since time domain of spectrum hole follows duty cycles of vacancy and usage (R. Tandra, 2005), the time resources are highly correlated (R. Tandra,2005). Frequency of PU usage and distance to PU from fusion centre are sparsely correlated. As discussed in Chapter 6 of this thesis, while the former can be modelled as Gaussian and the latter can be modelled using Semivariogram.

7.5 Formulation of Update of 3DSS Table

Update of 3DSS routing table by infrastructure supported base station is an iterative process. Table is updated frequently to reflect spectrum agility of the CRMANET nodes as well as link states. Given that network base station does iterative assignment of resources denoted by r_i and the network throughput is denoted by t_i, one gets series of results for each allocation denoted by (r_i,t_i), (r_2,t_2), (r_3,t_3), (r_4,t_4)……… (r_n,t_n). Error function from this is defined in Equation (7.1):

$$E(w,b) = \frac{1}{n}\sum_{i=1}^{n} L\big(t_i, f(r_i)\big) + \alpha R(w) \tag{7.1}$$

Equation (7.1) refers to error in updating the resources to improve throughput of the network. In Equation (7.1)

L is a loss function which defines update model fitness (misfit)

α > 0 is a non-negative hyper parameter

R is the penalty function for regularization function, which penalizes the model complexity

n is number of samples

b is error parameter

Loss function L can be different for different techniques for classification. Since SVM is used in this research, hinge loss function is used for L, which is defined by:

$$L_i = \sum_{j \neq yi} \begin{cases} 0 & if\ s_{yi} \geq s_j + 1 \\ s_j - s_{yi} + 1 & Otherwise \end{cases} \tag{7.2}$$

Where s_i and s_j are losses at two different points of sample.

Regularization function can be defined either as L1 or L2 norm or Elastic net, which are defined as follows:

L1 norm is defined by:

$$R(\omega) = \frac{1}{2}\sum_{i=1}^{n} \omega_i^2 \tag{7.3}$$

Where ω is a weight used in Equation (7.1).

L2 norm is defined by:

$$R(\omega) = \frac{1}{2}\sum_{i=1}^{n} |\omega_i| \tag{7.4}$$

L2 norm is used when the expected solution is sparse.

Elastic norm which is hybrid of L1 and L2 norm is defined as:

$$R(\omega) = \frac{\rho}{2}\sum_{i=1}^{n}\omega_i^2 + (1-\rho)\sum_{i=1}^{n}|\omega_i| \qquad (7.5)$$

Where ρ is parameter related to L1 norm.

The primary aim of updating the route table of 3DSS based CRMANET node is to minimize the error function in Equation (7.1), by choosing appropriate loss function and regularization function. To optimize this, there is a need to arrive at optimal w_i in Equation (7.1) through iterative process. Since the problem is unconstrained, unconstrained optimization solution is made use of. SGD is one of the most commonly used unconstrained optimization solution in many iterative problems like deep learning and mesh networks.

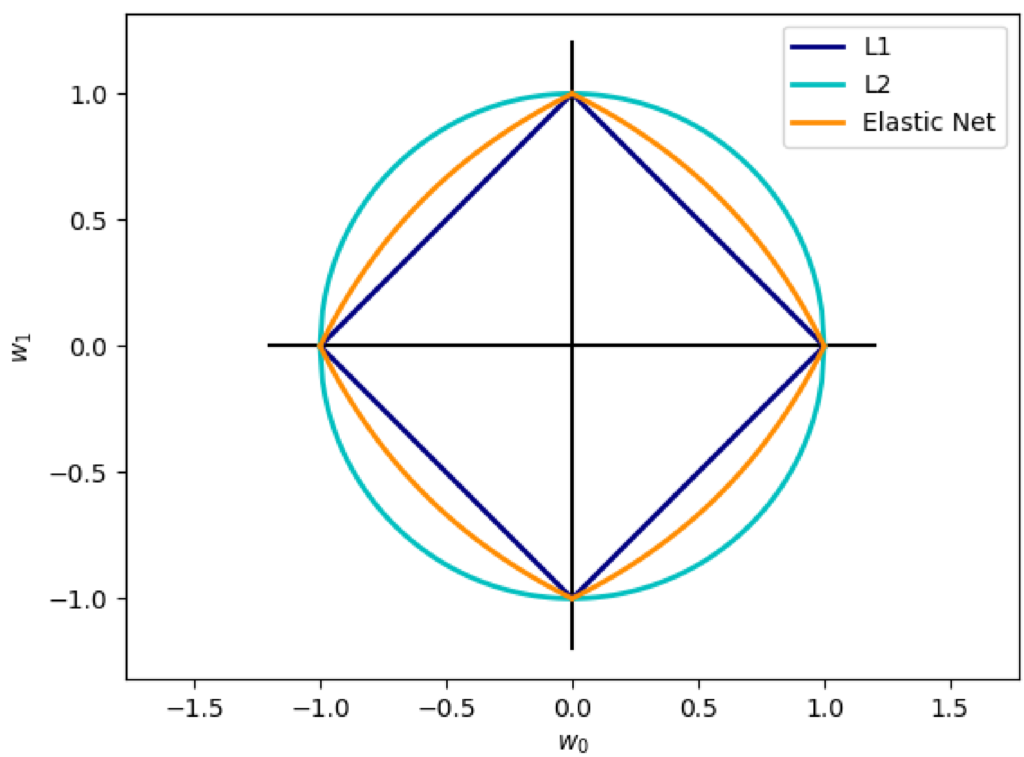


Figure 7-12 SGD Penalties (*Scikit*, 2010)

Figure 7.12 shows contours of different regularization terms when R(ω) = 1. Regularization in machine learning works towards biasing the parameters of machine learning models towards an optimal value. Biasing is achieved through adding tuning parameters. Among these parameters are L1, L2 and Elastic penalties. L1 regularization penalty is equal to magnitude of model coefficients and thus limiting their values. L1 penalty sometime results in sparse models. L2 regularization adds penalty equal to square root of model coefficient. L2 regularization will not yield sparse model. Elastic regularization is a combination of both L1 and L2.

7.6 Table Update Optimization Using Stochastic Gradient Descent (SGD)

Optimal update of table using 3D SS routing protocol is an unconstrained optimization problem. As was analyzed in chapter 3, vanilla gradient descent converges to local optimum when used with energy detector in a CRMANET setup. SGD is a suitable optimization technique used in unconstrained optimization problem. Obtained optimal routing table is a constrained or weakly constrained optimization problem. Loss function for optimal routing problem can be defined jointly or independently. This is because, it can be justified that time, frequency, space resources for CRMANET usage are linearly independent. SGD algorithm is used in this research to update time, frequency and distance model parameters separately in route tables.

The model parameter of the 3DSS detector is updated according to rules given by:

$$\omega_t \leftarrow \omega_t - \eta_t \left(\left(\alpha \frac{\partial R(\omega_t)}{\partial \omega_t} \right) + \left(\frac{\partial L(\omega_t^T r_i + b, t_i}{\partial \omega_t} \right) \right) \tag{7.6}$$

$$\omega_f \leftarrow \omega_f - \eta_f \left(\left(\alpha \frac{\partial R(\omega_f)}{\partial \omega_f} \right) + \left(\frac{\partial L(\omega_f^T r_i + b, t_i)}{\partial \omega_f} \right) \right) \tag{7.7}$$

$$\omega_d \leftarrow \omega_d - \eta_d \left(\left(\alpha \frac{\partial R(\omega_d)}{\partial \omega_d} \right) + \left(\frac{\partial L(\omega_d^T r_i + b, t_i)}{\partial \omega_d} \right) \right) \tag{7.8}$$

Where η_t, η_f, η_d are learning rates which control the step-size of the 3D parameters. ω_t is the parameter to model the SVM in the time domain. ω_f is the parameter to model the SVM in the frequency domain. ω_d is the parameter to model the SVM in the time space or distance.

For each of three domains (d, t, f), separate SGD is executed to collect the error and update the resource map. Once resource map is updated, the routing table is populated with latest resources. The step size or learning rate is proportional requirement of update frequency of route table.

7.6.1 Simulation Setup and Simulation Results of 3DSS

The simulation setup of 3DSS routing algorithm involves producing training labelled data of the resource allocation, table update and the resulting throughput of the CRMANET network. The updates from micro 3DSS spectrum hole detector in space, time and frequency, are updated to base station. Triplet (d, t, f) is stored as resource map. Each resource map is a snapshot of all updates from all the nodes in its range of communication and control of overlay messages. The difference between two updates can be termed as update gradient, denoted by (Δd, Δt, Δf). This is an increment compared to previous update. With this difference, the network throughput is modelled by using active CRMANET nodes updating their communication utilization to the fusion centre. The throughput of the network is calculated with cumulative throughput of all nodes in sub network and then cumulative throughput of all sub networks. The resource map allocation and hence routing table updates are compared with the resulting throughput. Series of pairs of (r_i, t_i), where ri can be modelled as:

$$r_i(\omega_t, \omega_f, \omega_d) = t_i\omega_{ti} + f_i\omega_{fi} + d_i\omega_{di} \qquad (7.9)$$

Where, $\omega_t, \omega_f, \omega_d$ are the update parameters in time, frequency and space dimensions? For each spectrum sensor output of (d, t, f) resources, $\omega_t, \omega_f, \omega_d$ is updated through SGD to form optimal table update. Update parameters are continuously adjusted until stable throughput of network is attained. Considering millions of such updates are possible, SGD theoretically does not converge to local minimum. Once the updates of this network parameter are small, frequency or interval of updating of the routing table can be reduced. For availability of field data, random sensing data is generated, and throughput is calculated for each resource triplet. Same is passed into 3D SGD separately in time, space and frequency version, until optimal parameters for η, ω, α are obtained in each domain. Updates will be smaller as cumulative error would saturate versus update and ω is stable and hence the simulation can be stopped. More complex scenarios can be created with many subnets and modelling of interference injection. (E.T. Docket No. 10-237, 2002) suggests 80% of unused spectrum across, time, space and frequency. Assuming the error rate in routing of CRMANET is 0, one can increase spectral efficiency by 400% by using all spectrum for data communication. However, considering MANET cannot exploit all 80% of unused spectrum and as indicated in (Ian F. Akyildiz, 2009) and (Ejaz, W. ul Hasan,2011), link efficiency of MANET is not more than 30% due to the constant on requirement for link negotiation.

In this research link negotiation is completely offloaded to infrastructure and only data communication is D2D. Through such an approach, error in link negotiation can be brought down by correcting error in routing table by the fusion centre as shown in Figure

7.11. The algorithm for updating routing table is as shown in Figure 7.13. The error in routing table is calculated with respect to the forecasted availability of CR resources (d, t, f) and topology changes of the network in Figure 7.7.

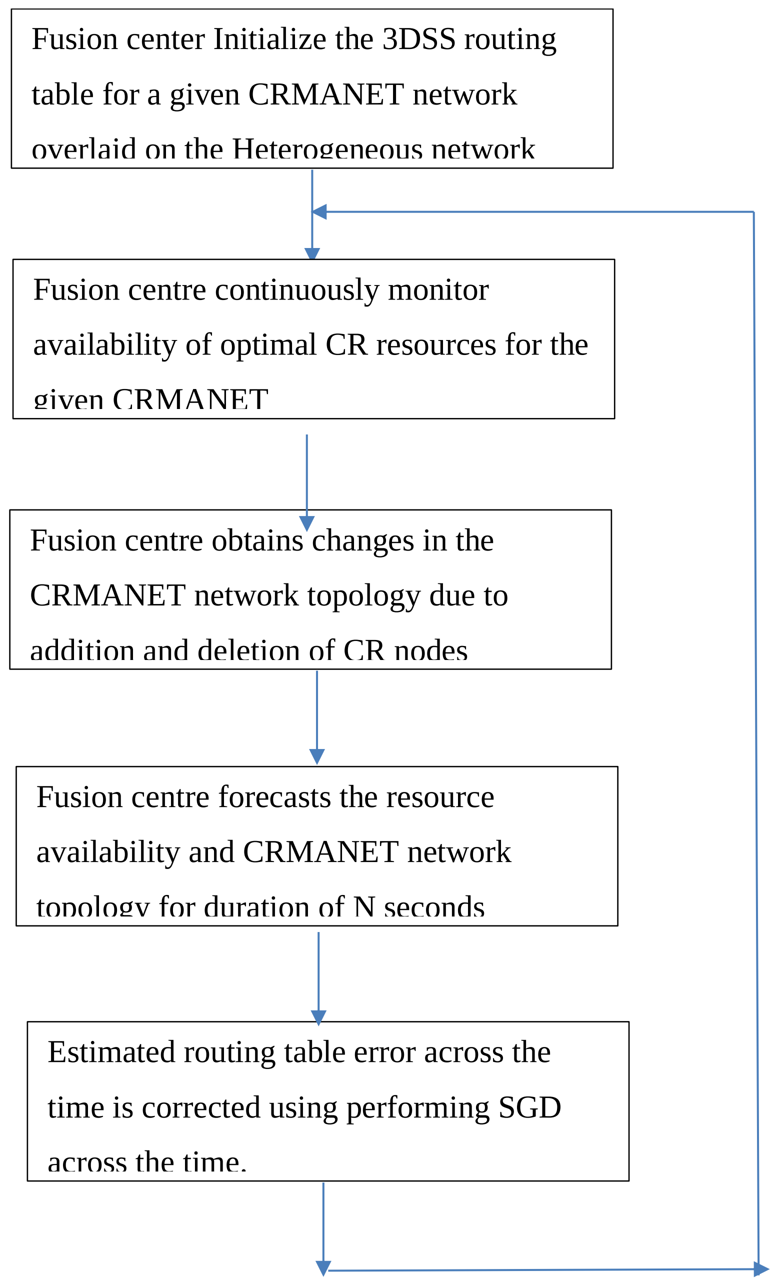


Figure 7-13 Algorithm to Routing Table using 3D SGD

With only 1-dimensional forecast of frequency domain, the CRMANET routing will not be feasible. On the contrary, it may insert more error in routing due to variance in time and space which may be static or wrongly captured.

7.7 Simulation of Routing Error Using 3D SGD

As defined in the simulation setup in section 7.6, simulation of the 3D SGD is carried with topology of MANET given in Figure 7.4. Routing table is updated by fusion centre as explained in section 7.6. The objective of simulation is to minimize updates to routing table when routing error back propagation is carried out by fusion centre.

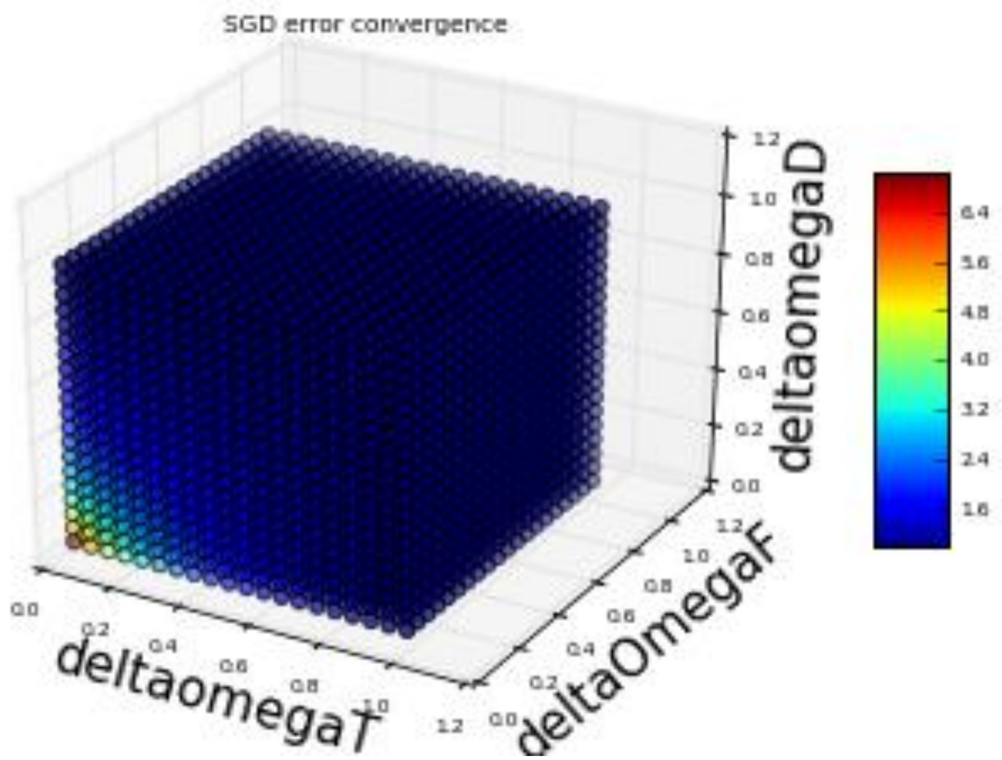


Figure 7-14 Convergence of Δωt, Δωf, and Δωd,

As shown in Figure 7.14 green and yellow shows all three errors in parameters converge close to zero after many backpropagations of errors in time. Assumption made in this research is that CRMANET topology would not change much in the time required for number of iterations required to converge the parameters ω_t, ω_f and ω_d. If this assumption hold, one can achieve close to 400% increase in spectral efficiency due to complete usage of 100% of spectrum available.

7.8 Changes in the Heterogeneous Base Station Structure to Accommodate Overlay of MANET

Overlay of MANET on heterogeneous network requires the interfaces of both infrastructure node and the CRMANET node to be significantly modified, both in hardware and software. Implementation of multithreaded, multi instance SGD on the base station is a must for overlaying CRMANET onto heterogeneous network. The base station also needs to have dedicated broadcast channel allocated for table update.

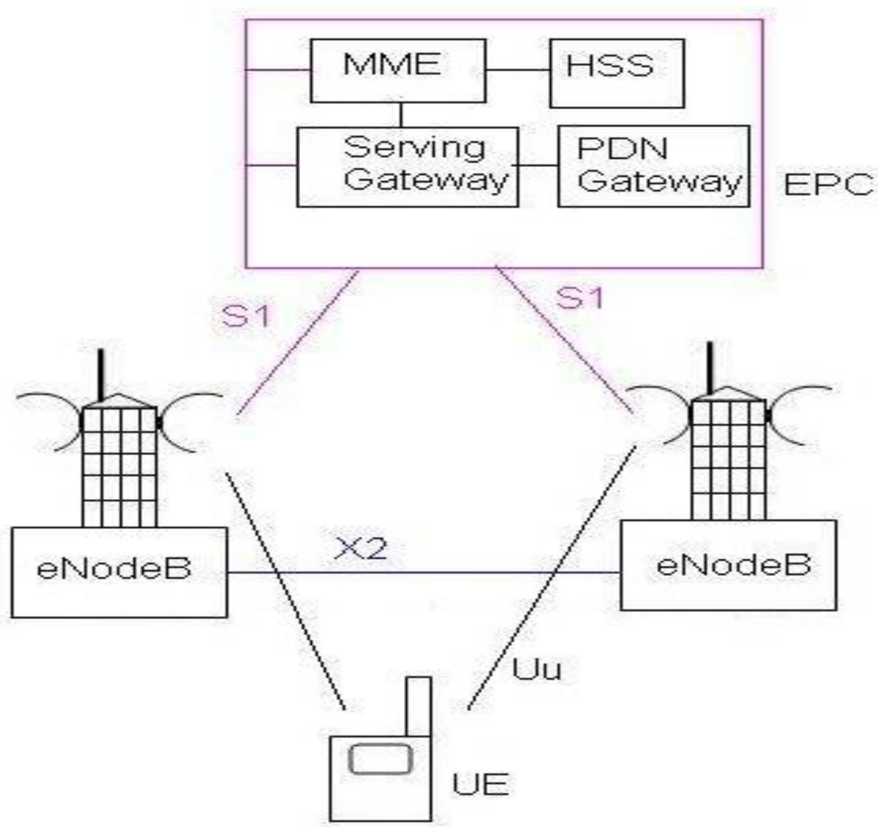


Figure 7-15 e NodeB Architecture (RFworld, 2010)

As shown in Figure 7.15, apart from EPC interfaces, base station or eNodeB has to implement additional CRMANET update interface. This transforms the interfaces as shown in Figure 7.16. Addition of CRMANET control interface is a requirement to make overlay of CRMANET interface work.

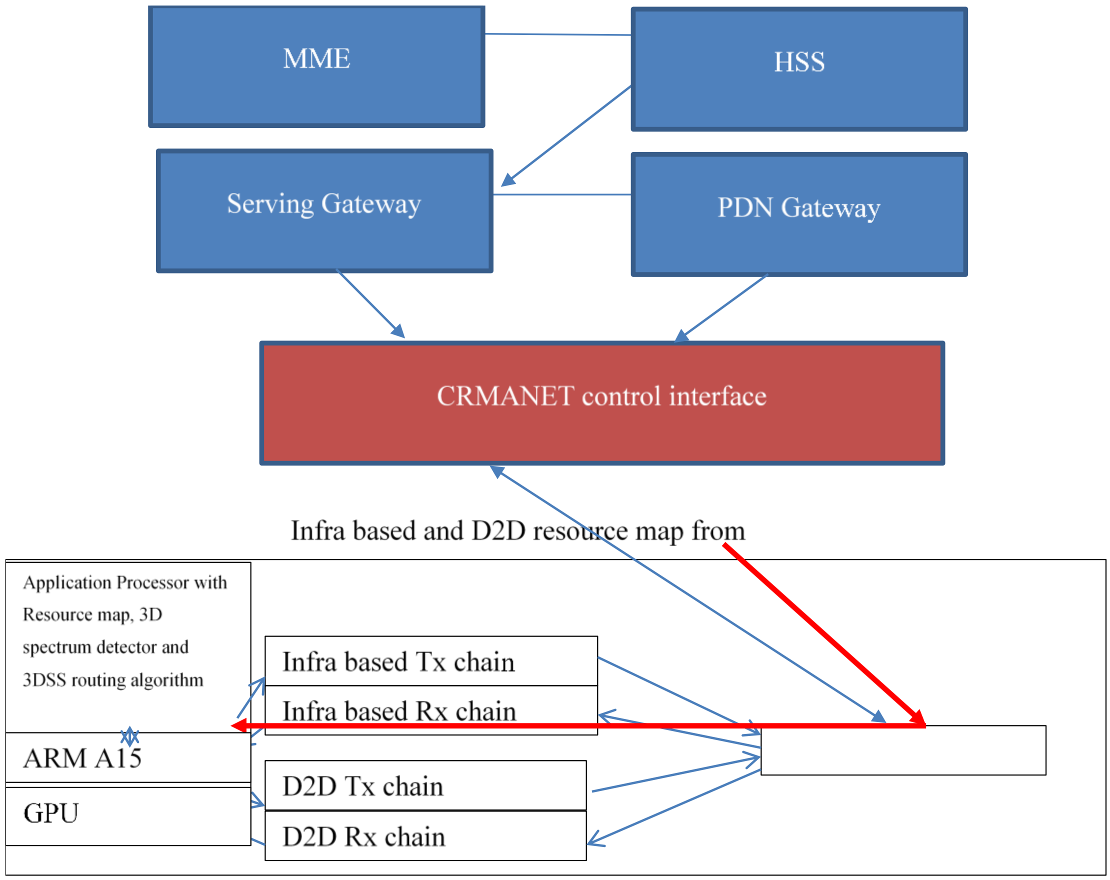


Figure 7-16 Changes to CRMANET Node for Same Device Being PU and CR Node

7.9 Summary

This chapter has presented a simulation model for overlaying of CRMANET on a heterogeneous network. This chapter has discussed the key differences between the conventional MANET, CRMANET and CRMANET overlaid on a heterogeneous network. The chapter has presented the significant additional details required in the update of route table of CRMANET when overlaid on a heterogeneous network. Without overlay CRMANET will be susceptible to flooding due to frequent changes in the link information and frequent update is required for table based routing. A novel 3DSS routing algorithm used for 3D spectrum sensing based CRMANET is also proposed in this chapter.

Combination of 3DSS routing and updating table using the infra based heterogeneous base station helps in overcoming the flooding of broadcast messages by majority or all of CRMANET nodes. This chapter has also discussed the implementation of DSDV protocol on MANET overlaid on heterogeneous network. Two schemes for updating the payload of broadcast channel considered in this chapter are node number based round robin update and OFDM shared symbol for table update. If the D2D communication is used for low power sensor network, first method of node number based round robin time division multiplexing with multi frame structure) can be used. If faster network implementation of OFDM on Wi-Fi, ZigBee and Bluetooth are used, the method of shared OFDM symbol can be a choice. Further OFDM based networks require much less synchronization compared to CDMA based networks. This chapter has clearly brought out an acute need for new routing protocol to accommodate spectrum agility. A novel routing protocol which is termed as 3-Dimensional Spectrum Sensing (3DSS) routing protocol is proposed in this chapter. This chapter has presented the formulation of update of 3DSS table. This chapter has discussed the optimization of update of route table using SGD. Use of SGD optimization algorithm will avoid converging to local minima and hence overcomes the issue of sub optimal throughput of CRMANET. Since control signaling is through overlay, CRMANET can use 80% of the bandwidth for data communication thereby increasing the available bandwidth. Since available bandwidth is increased by 30%, spectral efficiency increases by 30%. In lieu of 3DSS routing, spectral efficiency increases by 400% due to exploitation of low interference temperature. Hence with an overlay of CRMANET on heterogeneous network and deployment of 3DSS routing, total spectral efficiency improvement is 230% relative to that with CRMANET.

Performance comparison between 1D spectrum sensing based CRMANET without overlay CRMANET) and 3DSS-3DSS routing algorithm based CRMANET with an overlay on heterogeneous network is shown in Table 7.4. As was discussed earlier, the available bandwidth of CR reduces with the introduction of MANET. With the overlay of CRMANET on heterogeneous network with 3DSS and 3DSS routing algorithm, significant enhancement in usable bandwidth can be achieved. This is seen through a usable bandwidth of 500 MHz of CRMANET overlaid on heterogeneous network using 3DSS. The spectral efficiency of CRMANET overlaid on heterogeneous network with 3DSS is 24 folds higher than that with 1D spectrum sensing based CRMANET without overlay. The specified spectral efficiency in LTE is 30 bits/sec/Hz. With the deployment of 3DSS, 3DSS routing and overlay on heterogeneous networks, the spectral efficiency of the network far exceeds the requirement of LTE.

Table 7.4 Performance Comparison of CRMANET With and Without 3DSS and 3DSS Routing Algorithm and Overlay on Heterogeneous Network

Performance metrics	**1D spectrum sensing based CRMANET without overlay**	**3DSS and 3DSS routing algorithm based CRMANET with overlay on heterogeneous network**
Usable bandwidth for CRMANET	100 MHz	500 MHz
Range of Probability of false alarm at fusion centre	0.5 to 0.1	0.01 to 0.0001
Range of Probability of missed detection at fusion centre	0.5 to 0.1	0.01 to 0.0001
Spectral efficiency (bits/sec/Hz)	5	120

Chapter 8 Conclusions and Suggestions for Future Work

This chapter summarises research studies presented in this thesis. It highlights the summary of inferences drawn from the research and the key results of the proposed research studies. This chapter also suggests potential for further research emerging from the perspectives of research progress achieved in this thesis as well as from the considerations of recent developments in the core and peripheral domains related to the research topic of this thesis.

8.1 Summary

This thesis presents the novel system architecture and algorithms to obtain higher spectral efficiency by increasing the usable bandwidth of CR networks. The increased usable bandwidth and the enhanced spectral efficiency are achieved through controlled co-operative spectrum sensing. Since controlled co-operative spectrum sensing enables estimation of distance of PU to fusion centre, resource allocation required for sensing and communication can be performed optimally thereby improving the usable bandwidth for communication. 3D spectrum sensing aided by SVM decreases the probability of false alarm and the probability of missed detection of PU. Thus, the 3D spectrum sensing not only increases the throughput of the network but also reduces the interference to PU. Through mathematical modeling, simulation and analysis of 3D spectrum sensing, this thesis has contributed to the research in CR. Application of machine learning is also explored by formulation of 3D spectrum sensing using SVM kernels.

Overlaying the MANET on heterogeneous networks enabled the 3DSS routing algorithm to enhance the potential success in the deployment of CRMANET. MANETs are prone to hidden node problem when associated with a single node spectrum sensing for the detection of presence of PU. Controlled co-operative spectrum sensing provides system architecture and algorithms to overcome the issue of hidden node. With an assumption of equal distribution of lower and higher frequency bands for communication, controlled co-operative spectrum sensing through regression on path loss model increases available bandwidth for CR communication by 100%,.

Using 3DSS, it is shown through simulation that 3D spectral hole detection can be modelled accurately. By applying the concept of 3D spectral hole detection, probability of false alarm and also the probability of missed detection are reduced by a factor of 3. When MANET is deployed using an overlay on heterogeneous networks, spectrum efficiency of CRMANET is improved by 100% due to the usage of 3DSS routing protocol facilitated by MANET.

8.2 Conclusions

Details of the mathematical modelling, simulations and inferences from simulations and system analysis are discussed in following sub sections.

8.2.1 Controlled Co-Operative Spectrum Sensing Using Path Loss Model

Conventional spectrum sensing techniques using a single sensor and the standalone signal processing techniques may not be sufficient to improve the spectral efficiency of the network. This thesis has presented a new concept of controlled co-operative spectrum sensing using binary regression on wireless path-loss curves. With an assumption that the PU is operating conforming to the defined mobile communication specifications, the distance of the PU from the fusion centre can be accurately estimated applying controlled co-operative sensing, With the estimated distance of PU and the algorithm for allocation of resources needed in CR, the SNR of the sensing channel is improved over conventional co-operative spectrum sensing. As shown through the simulation results, with improvement of the SNR of the channel, probability of false alarm drops which in turn improves the throughput of CR network. Also incorporating this improvement in Equation

(3.11). 50% improvement in the spectral efficiency is evident with controlled co-operative sensing relative to that obtained through conventional single sensor spectrum sensing. This thesis has also discussed cumulative probabilities at the fusion centre**.** An expression for the determination of the optimal value of CR nodes ‘N’ required for co–operative spectrum sensing to meet the specified threshold of statistical significance is also derived. With the knowledge of CSI, distance of PU and frequency bands, this thesis proposes an algorithm for allocating frequency for sensing and frequency for communication. This thesis also reveals that the allocation of the frequency in accordance with the estimated distance of the PU from the fusion centre provides significant improvement in usable bandwidth for both CR communication and spectrum sensing. This enables to allocate the frequencies for sensing and communication such that usable bandwidth for CR network increases by 100%. Proposed analysis reveals that spectral efficiency increases linearly with increase in available or usable bandwidth.

This thesis also presented an algorithm to assign nodes for multiband frequency sensing based on CSI and distance of PU from fusion centre. The thesis has also discussed the operating region and power control of CR nodes using controlled co-operative spectrum sensing**.** Such an analysis will result in minimization of interference to PU. Distance based controlled co-operative sensing proposed in this thesis conforms to the Interference Temperature (IT) model suggested by FCC. Distance based controlled co-operative sensing can model the IT with better accuracy.

The discussions covered under this sub section answer the research questions 1, 2 and 3.

1. Does controlled co-operative spectrum sensing performs better than the co-operative spectrum without a way to allocate resources?
2. Is it possible to increase available bandwidth and usable bandwidth in a wireless network by using CR techniques?
3. What are the effects of estimation of distance of PU from the fusion centre on the resource allocation and spectrum efficiency improvements?

8.2.2 3-Dimensional Spectrum Sensing (3DSS)

This thesis has presented the concept of 3 Dimensional spectrum sensing instead of a conventional 1-D spectrum sensing. The proposed 3-D spectrum hole detection considers time and space in addition to frequency domain. The thesis has presented the system level probability of missed detection and probability of false alarm applicable for 3D spectrum sensing. The probability of missed detection in 3-D spectrum hole detector is a combination of 3 variables and has 3 degrees of freedom. 3-D spectrum hole detection technique exhibits lower probability of missed detection. It is shown that the adaptation of 3-D spectrum hole detection leads to decrease in the probability of missed detection by a factor of 100. The resulted decrease in the probability of missed detection of PU directly translates to reduction in interference temperature at PU. As a result there is an additional margin in new spectrum opportunity part of CR. It is proved that by assuming the proportionality constant for interference temperature and probability of missed detection to be logarithmic function, total usable bandwidth of CR network can be increased by a factor of 2 resulting in a 2 fold improvement in spectral efficiency of the network. This is the key result using the 3-D spectrum detector in place of 1D or 2D spectrum detector. As a figure of merit for the assessment of improvement in the spectral efficiency because of CR enabled network, a term called CR gain is proposed. CR gain is defined as a ratio of spectral efficiency of the network with the deployment of CR to the spectral efficiency of network without CR. Thus the CR gain can be termed as a relative measure of the improvement in the spectral efficiency of the network in lieu of it being CR enabled.

3D spectrum sensing has offered significant flexibility in allocating resources for an overlaid network. The structure of resource blocks with 3 dimensional factors will result in an optimal Q_{spec} compared to that with 2-D or 1-D detection. With resource map available to infrastructure-based network, allocation of resources to CR communication is better with 3-D structures than compared to 1-D or 2-D structures. This thesis has also presented a generic setup for 2-level spectrum hole detection using macro and dynamic spectrum hole detection. The same model is applied to all the 3 domains of 3D spectrum hole detector. SVM with 3D RBF kernel is used to estimate the spectrum holes. 3D RBF is used to transform the data samples collected from domain comprising space, time and frequency and then to convert it to feature space. Concept of the Qspec constraint has been generalized for improving the spectrum quality of PU in the presence of overlay of CR. Providing 3-dimensional resource map has further enabled fine granular resource allocation for both sensing and CR communication. Use of machine learning techniques improved the accuracy of PU detection by 1000 %, due to detection in 3 dimensions of space, time and frequency independently

In view of the enormity of end users of the commercial wireless communication devices and systems, an in-depth analysis of spectrum usage truly belongs to the category of big data. Since there is availability of large-scale spectrum usage data, machine learning has been applied to improve the system performance of CR network. SVM is used in 3-dimensions of space, time and frequency to obtain accurate resource maps. These maps is used for the allocation of resources for CR communication and spectrum sensing (detection of PU). The prior available distribution in space, time and frequency is used to train the SVM in 3-dimensions. The probabilities of missed detection of PU and false alarm are directly proportional to the classification error of SVM. Improvements in the classification accuracy of machine learning algorithm decrease the probability of missed detection of PU. Apart from the basic machine learning technique used in the spectrum sensing, the structure of 3D detector by construct reduces the probability of missed detection compared to 1D or 2D spectrum hole detector.

The discussions presented in this sub sections answer the research questions 5, 7 and 10.

5 What is the effect of using machine learning on the spectrum sensing techniques?
7 Can the dimensions of space and time be used in spectrum sensing, although some research studies define spectrum hole across space and frequency?

10 Can simple machine learning techniques be applied to improve spectrum efficiency in CR MANET systems overlaid on heterogeneous networks?

8.2.3 Overlaying MANET on Heterogeneous Network

This thesis has developed a simulation model for overlaying of CRMANET on a heterogeneous network. In particular this chapter has discussed the key differences between the conventional MANET, CRMANET and CRMANET overlaid on a heterogeneous network. The thesis has presented the significant additional details required in the update of route table of CRMANET when overlaid on a heterogeneous network. Without overlay, CRMANET will be susceptible to flooding of messages due to frequent changes in the link information and frequent update required for table based routing.

The thesis has clearly brought out an acute need for new routing protocol to accommodate spectrum agility. A novel routing protocol which is termed as 3-Dimensional Spectrum Sensing (3DSS) routing protocol useful for 3D spectrum sensing based CRMANET is proposed in this thesis. A formulation for update of 3DSS table is also proposed in this thesis. Combination of 3DSS routing and updating of table using the infra based heterogeneous base station helps in overcoming the flooding of broadcast messages by majority or all of CRMANET nodes. This thesis also discussed the implementation of DSDV protocol on MANET overlaid on heterogeneous network. This thesis analyses the optimization of update of table using SGD. Use of SGD optimisation algorithm will avoid converging to local minima and thus overcomes the sub optimal throughput of CRMANET.

For efficient functioning of MANET, cross layered control plane is proposed with an over lay of control plan onto infrastructure based heterogeneous network. With an overlay of control information on heterogeneous network, signalling in MANET is found to be more reliable. This thesis provides the solution of using unlicensed band for signalling in

MANET. By overlaying MANET control onto heterogeneous network with resource map architecture explained in Chapter 6, signalling in MANET is made more robust. This enables the successful deployment of CRMANET. For the proposed CRMANET of this thesis, the predefined dynamic resource map is used for routing in CRMANET. This in turn increases the total available bandwidth for CR communication. This thesis emphasises that spectral efficiency of CRMANET overlaid on the heterogeneous network can be enhanced by 100%.

Through the discussions presented in this sub section, the research questions 4, 6 and 9 have been answered.

4 Can CR exploit heterogeneity in network interfaces to increase spectral efficiency?

6 What is the effect of the overlay of MANET on heterogeneous networks to enable the CR applications of MANET?

9 What kind of resource structure is required for overlaying CR enabled MANET on heterogeneous networks?

8.2.4 A 3DSS Routing in MANET

This thesis proposes a 3DSS table based routing algorithm to provide resource map for D2D communication in CR. Unlike traditional table based routing algorithm, 3DSS routing algorithm incorporates CR resources and updates them dynamically. The link update and maintenance are directly related to Qspec improvements and compliance. SGD algorithm is used as an optimisation tool for link maintenance and update of link information. SGD optimisation algorithm reduces the risk of converging to local optimum as compared to Gradient Descent (GD) thereby overcoming the issue of sub optimal throughput of CRMANET. Apart from reducing the risk of converging to local optimum, SGD also provides better routing in D2D network. SGD results in reduction of overall number of updates. This thesis has discussed the optimization of table update using SGD. Since control signalling is through an overlay, CRMANET can use 80% of the bandwidth for data communication thereby increasing the available bandwidth. Since available bandwidth is increased by 30%, spectral efficiency also increases by 30%. In lieu of 3DSS routing, spectral efficiency increases by 400% due to exploitation of low interference temperature. Hence with an overlay of CRMANET on heterogeneous network and deployment of 3DSS routing, total spectrum efficiency improvement is 230% relative to that with CRMANET. This subsection provides an answer to research question 8. How does routing algorithms get modified in MANET, when enabled for CR?

8.3 Suggestions for Future Work

The perennial progress of research in any field is attributed to the philosophical statement that "Research is neither a first step nor a last step, but is always a next step". One of attributes of a good research thesis hinges on its ability to provide a gate way for continuation of research aimed at the solution to the dominant issues which may pertain to core or peripheral aspects of the research thesis. This section presents a few topics which are of considerable importance to the research domain of this thesis.

8.3.1 Transmission Power Control in CR

Although controlled co-operative spectrum sensing greatly improves available spectrum for communication, it has its limitation in terms of macro visibility of spectrum holes as well as the underlying hypothesis of the path loss model to measure the presence of PU. Hypothesis based on path loss model is rather static and cannot be applied across time, space and frequency. This hypothesis does not consider the time aspect of spectrum hole.
Further research in power control of CR transmission can consider the following aspects.

11 Relation between sensitivity of PU and sensitivity of CR
12 Dynamic interference budgeting
13 Transmit power of CR in terms of interference, CR sensitivity and sensitivity of PU

14 Block diagram of the CR modem

15 Multiband CR detection

8.3.2 Deep Learning and Reinforcement Learning Algorithms in CR

This thesis has dealt with the techniques for the enhancement of spectral efficiency in wireless communication through CR technology. In particular, spectrum agility part of CR is used to improve the spectral efficiency. The solution proposed for the improved spectral efficiency involves both novel signal processing and networking techniques. SVM, a basic machine learning algorithm has been extensively applied in the analytical formulations of this thesis. During the elapsed time duration of this thesis, there have been significant breakthrough and advancements in the broad domain of machine learning algorithms. Deep learning has emerged as the mainstream machine learning technique, which can approximate many non-linear functions. Other AI technologies like reinforcement learning is evolving as topic of considerable research interest. Analytical and simulation studies invoking deep learning and reinforcement learning algorithms will aid to exploit the spectrum agility to the fullest extent and one can anticipate further enhancement in spectral efficiency of CR enabled communication devices.

8.3.3 Deep Q Networks in CR

In this research only a basic model of SVM algorithm is used. More complex deep convolution networks can be used to enable the spectrum agility. Newer techniques like deep reinforcement learning based on deep Q networks can provide superhuman control (Volodymyr Mnih, Nature 2015) for spectrum agility. Deep reinforcement learning is an exciting and promising technology for long term optimization using the deep networks. Long term optimization of the spectrum efficiency can be achieved through deep reinforcement learning in combination with very high sensitive receivers to detect the spectrum hole. This can be accomplished by more heterogeneity in the network. Recently defined LTE standard (3GPP-LTE) suggests enabling the spectrum agility. The combination of deep learning algorithms and deep Q network will lead to a more efficient and highly dynamic intelligent system in Radio Resource Management (RRM) required in CR.

REFERENCES

3GPP-LTE, (2015), http://www.3gpp.org/technologies/keywords-acronyms/98-lte

5G mobile standards (2011), *https://5g.ieee.org/standards/standards-database*

A. N. Zadeh, B. Jabbari, R. Pickholtz, and B. Vojcic, (2002) "Self-Organizing Packet Radio Ad hoc Networks with Overlay", *IEEE Communication Magazine, Vol. 40, No.6, pp. 144-157*

Abhinaba Banerjee; Sushanta Das, (2014) "A Review on Security Threats in Cognitive Radio", *Wireless Communications, Vehicular Technology, Information Theory and Aerospace & Electronic Systems (VITAE), Digital Object Identifier: 10.1109/VITAE.2014.6934417*

*Ahmed M. Jasim ; Haidar N. Al-Anbagi (2017) "*A comprehensive study of spectrum sensing techniques in cognitive radio networks", *Current Research in Computer Science and Information Technology (ICCIT)*

Ahmad Saad ; Barbara Staehle ; Rudi Knorr (2016) "Spectrum prediction using hidden Markov models for industrial cognitive radio*", Wireless and Mobile Computing, Networking and Communications (WiMob), 2016 IEEE 12th International Conference*

Aluru, P.; Rajpurohit, J.; Agarwal, M.; Rao, S.V.R.K.; Singh, G. (2010) "Improvement in Total Sensing Time of the Receiver in the Cognitive Radio "Advances *in Recent Technologies in Communication and Computing (ARTCom), Digital Object Identifier: 10.1109/ARTCom.2010.27*

Anh Hoang; Ying-Chang Liang; Yuncheng Zeng, (2010) "Adaptive Joint Scheduling of Spectrum Sensing and Data Transmission in Cognitive Radio Networks", *IEEE Transactions on Communications, Volume: 58, Issue: 1, Digital Object Identifier: 10.1109/TCOMM.2010.01.070270*

Anh Tuan Hoang; Ying-Chang Liang (2007) "Adaptive Scheduling of Spectrum Sensing Periods in Cognitive Radio Networks", *Global Telecommunications Conference, 2007. GLOBECOM '07. Digital Object Identifier: 10.1109/GLOCOM.2007.592*

Aripin, N.M.; Rashid, R.A.; Fisal, N.; Yusof, S.K.S (2009) “Evaluation of Required Sensing Time for Multimedia Transmission over Cognitive Ultra-Wideband System”, *Ultra-Modern Telecommunications & Workshops. ICUMT '09. International Conference, Digital Object Identifier: 10.1109/ICUMT.2009.5345408*

B. L. Mark and A. O. Nasif (2008) “Estimation of Interference-Free Transmit Power for Opportunistic Spectrum Access*,” in Proc. of IEEE Wireless Communications and Networking Conference (WCNC), Las Vegas, NV, USA, pp. 1679–1684. Digital Object Identifier: 10.1109/WCNC.2008.300*

B. Pursley; Thomas C. Royster (2008) “Low-Complexity Adaptive Transmission for Cognitive Radios in Dynamic Spectrum Access Networks”, *IEEE Journal on Selected Areas in Communications, Volume: 26, Issue: 1, Digital Object Identifier: 10.1109/JSAC.2008.080108*

Babadi, B.; Tarokh, V (2008) “The Impact of Spectrum Sensing Time on the Performance of the GADIA Algorithm”, New *Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 3rd IEEE Symposium, Digital Object Identifier: 10.1109/DYSPAN.2008.56*

Brett Kaufman, Jorma Lilleberg, and Behnaam Aazhang, (2013) “Spectrum Sharing Scheme Between Cellular Users and Ad-hoc Device-to-Device Users”, *IEEE Transaction on Wireless communications, Vol.12, No.3, pp 1038 – 1049, Digital Object Identifier: 10.1109/TWC.2012.011513.120063*

C. E Perkins and P Bhagawat (1994) “Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for Mobile Computing”, *Proceedings of ACM SIG-COMM, pp. 234-244, Digital Object Identifier: 10.1145/190314.190336*

C. Siva Ram Murthy and B.S. Manoj (2004) “Ad Hoc Wireless Networks: Architectures and Protocols” *Prentice Hall Professional Technical Referenceupper Saddle River, NJ 07458*

Carla-Fabiana Chiasserini; Maria-Gabriella Benedetto; Ping Zhang ; Xiangpeng Jing, (2012) “Cognitive Radio Networks: A Practical Perspective”, *IEEE Wireless Communications (Volume: 19, Issue: 4), Digital Object Identifier: 10.1109/MWC.2012.6272417*

Chen Guo, Tao Peng, Yuan Qi, Wenbo Wang (2009)" Adaptive Channel Searching Scheme for Cooperative Spectrum Sensing in Cognitive Radio Networks", *2009 IEEE Wireless Communications and Networking Conference (2009), Digital Object Identifier: 10.1109/WCNC.2009.4917558*

Chengshi Zhao; Kyungsup Kwak (2010) "Joint Sensing Time and Power Allocation in Cooperatively Cognitive Networks", *Communications Letters, IEEE Volume: 14, Issue: 2 Digital Object Identifier: 10.1109/LCOMM.2010.02.092102*

Chin, Kwan-Wu Judge, John Williams, Aidan Kermode, Roger (2002) "Implementation Experience with MANET Routing Protocols"; *ACM SIGCOMM Computer Communication Review , Volume 32 Issue 5, Pages 49-59*

Dezre, (2018) https://www.dezyre.com/data-science-in-r-programming-tutorial/support-vector-machine-tutorial,

Dong Wei, Chunyan Feng, Caili Guo, (2010) "A Sensing Time Saving Cluster-Based Cooperative Spectrum Sensing Scheme", *Communication Technology (ICCT), 12th IEEE International Conference, Digital Object Identifier: 10.1109/ICCT.2010.5689097*

Dong-Jun Lee; Myung-Sung Jang, (2009) "Optimal Spectrum Sensing Time Considering Spectrum Handoff Due to False Alarm in Cognitive Radio Networks ",*Communications Letters, IEEE Volume: 13 , Issue: 12 Digital Object Identifier: 10.1109/LCOMM.2009.12.091448*

Dongmei Shu; Jinkuan Wang; Bin Wang (2010) "A Dual-Threshold-Based Optimization of Spectrum Sensing Time", *Computer Design and Applications (ICCDA), 2010 International Conference on Volume: 4 Digital Object Identifier: 0.1109/ICCDA.2010.5540724*

E.T. Docket No. 10-237 (2002) 'Promoting More Efficient Use of Spectrum Through Dynamic Spectrum Use Technologies', *Federal Communications Commission*

Ejaz, W. ul Hasan, N.; Hyung Seok Kim; Azam, M.A (2011) "Fully Distributed Cooperative Spectrum Sensing for Cognitive Radio Adhoc Networks" *Frontiers of Information Technology (FIT), Digital Object Identifier: 10.1109/FIT.2011.10*

Ekram Hossain; Vijay Bhargava (2007) "Cognitive Wireless Communication Networks, Springers Publication", *ISBN 978-0-387-68830-5 e-ISBN 978-0-387-68832-9*

ET Docket No. 02,135 (2002) "Spectrum Policy Task Force," *Federal Communications Commission*

FCC 03-289 (2003), "Establishment of an Interference Temperature Metric to Quantify and Manage Interference and to Expand Available Unlicensed Operation in Certain Fixed, Mobile and Satellite Frequency Bands", *Federal Communications Commission*

Fu, Xiuhua Zhou, Wenan Xu, Junli Song, Junde (2007) "Extended Mobility Management Challenges over Cellular Networks Combined with Cognitive Radio by using Multi-hop Network", *Software Engineering, Artificial Intelligence, Networking, and Parallel/Distributed Computing, Digital Object Identifier: 10.1109/SNPD.2007.172*

Ghosh, R.; Lerman, K. (2009) "Structure of Heterogeneous Networks", Computational *Science and Engineering, CSE '09. International Conference on Volume: 4 IEEE Conference, Digital Object Identifier:10.1109/CSE.2009.142*

Ghurumuruhan Ganesan ; Ye Geoffrey Li ; Benny Bing ; Shaoqian Li, "Spatiotemporal Sensing in Cognitive Radio Networks*", IEEE COMMUNICATIONS SOCIETY 2008, Digital Object Identifier: 10.1109/JSAC.2008.080102,*

Guangquan Chen, Yong Zhang, Mei Song Yinglei, Teng Ruijun, (2009) "Architecture and Behavioral Model for Future Cognitive Heterogeneous Networks", *Wireless Communications, Networking and Mobile Computing, Digital Object Identifier: 10.1109/WICOM.2009.5305008*

Guangquan Chen, Yong Zhang, Mei Song, Yinglei Teng, Ruijun Feng, (2009) "Architecture and Behavioral Model for Future Cognitive Heterogeneous Networks", *Wireless Communications, Networking and Mobile Computing, Digital Object Identifier: 10.1109/WICOM.2009.5305008*

H. Wu, C.Qiao, S. De, and O. Tonguz (2001) "Integrated Cellular and Ad Hoc Relaying Systems: iCAR," *IEEE Journal on selected Areas in Communications, Vol.19, Issue 10, pp. 2105-2115*

Haipeng Yao; Xuan Sun; Zheng Zhou; Liang Tang; Lei Shi (2010) "Joint Optimization of Subchannel Selection and Spectrum Sensing Time for Multiband Cognitive Radio Networks ", *Communications and Information Technologies (ISCIT), Digital Object Identifier: 10.1109/ISCIT.2010.5665173*

Hamdi, K.; Ben Letaief, K (2009) "Power, Sensing Time, and Throughput Tradeoffs in Cognitive Radio Systems: A Cross-Layer Approach", Wireless *Communications and Networking Conference, IEEE, Digital Object Identifier: 10.1109/WCNC.2009.4917914*

He, Jian; Xu, Changqing; Li, Li (2010) "Joint Optimization of Sensing Time and Decision Thresholds for Wideband Cognitive OFDM Radio Networks Wireless", *Mobile and Multimedia Networks, IET 3rd International Conference, Digital Object Identifier: 10.1049/cp.2010.0658*

Hubbard, Raymond; Bayarri, M.J. (2003), "P Values are not Error Probabilities", *University of Valencia*

Ian F. Akyildiz , Won-Yeol Lee, Kaushik R. Chowdhury (2009) "CRAHNs: Cognitive Radio Adhoc Networks", *Adhoc Networks archive Volume 7, Elsevier Science Publishers B. V. Amsterdam, The Netherlands, Pages 810-836, Digital Object Identifier :10.1016/j.adhoc.2009.01.001*

IETF RFC 2501 (1999) "Mobile Ad hoc Networking (MANET): Routing Protocol Performance Issues and Evaluation Considerations", *Internet Engineering Task Force*

Insook Kim; Dongwoo Kim, (2010) "Optimal Allocation of Sensing Time Between Two Primary Channels in Cognitive Radio Networks", *Communications Letters, IEEE Volume: 14, Issue: 4, Digital Object Identifier: 10.1109/LCOMM.2010.04.092464*

Jacques Palicot, Joseph Mitola III, Zander (Zhongding) Lei and Friedrich K Jondral (2012) "Ten Years of Cognitive Radio: State of the Art and Perspectives", *EURASIP Journal on Wireless Communications and Networking, Digital Object Identifier: 10.1186/1687-1499-2012-28*

Jantti, R.; Kerttula, J.; Koufos, K. ; Ruttik, K (2011) "Aggregate Interference with FCC and ECC White Space Usage Rules: Case Study in Finland", *New Frontiers in Dynamic Spectrum Access Networks (DySPAN), IEEE Symposium, Digital Object Identifier: 10.1109/DYSPAN.2011.5936252*

Javed, F.; Mahmood, A (2010) “The Use of Time Frequency Analysis for Spectrum Sensing in Cognitive Radios”; *Signal Processing and Communication Systems (ICSPCS), 4th International Conference*

Joe Bater, Hwee-Pink Tan, Kenneth N Brown, Colman O'Sullivan and Linda Doyle (2007) “An Interference Temperature Constraints Model for Spectrum Access in Cognitive Radio Networks”, *IEEE CogNet Workshop*

Joseph Mitola; Alireza Attar ; Honggang Zhang ; Oliver Holland ; Hiroshi Harada ; Hamid Aghvami, (2010) , Special issue on the "Achievements and the Road Ahead: The First Decade of Cognitive Radio", *IEEE Transactions on Vehicular Technology Vol. 59*

Joseph Mitola III (2000) “Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio Dissertation”, *Doctor of Technology Thesis, Royal Institute of Technology (KTH)*

Jun Ma ; Geoffrey Ye Li ; Biing Hwang Juang (2009) “Signal Processing in Cognitive Radio”, *Proceedings of the IEEE, Volume: 97, Issue: 5*

Kandeepan, S.; Giorgetti, A.; Chiani, M. (2010) “Time-Divisional Cooperative Periodic Spectrum Sensing for Cognitive Radio Networks *Communications”, (ICC), IEEE International Conference*

Kaushik R. Chowdhury; Ian F. Akyildiz*, (2008) “*Cognitive Wireless Mesh Networks with Dynamic Spectrum Access”*, IEEE Journal on Selected Areas in Communications*

Khandekar, A.; Bhushan, N.; Ji Tingfang; Vanghi, V. (2010) “LTE-Advanced: Heterogeneous Networks”, *Wireless Conference (EW), European IEEE conferences*

Kishor Singh; Sangman Moh, (2016), “Routing protocols in cognitive radio ad hoc networks: A comprehensive review” *Journal of Network and Computer Applications Volume 72, September 2016, Pages 28-37*

Lan Zhang ; Ying-Chang Liang ; Yan Xin (2008) “Joint Beamforming and Power Allocation for Multiple Access Channels in Cognitive Radio Networks”, *IEEE Journal on Selected Areas in Communications*

Lawton, B.; Murphy, C.C. (2010) “Coarse-fine spectrum sensing for Cognitive Radio for Minimum Sensing Time”; *Signal Processing and Communication Systems (ICSPCS), 4th International Conference on Digital Object Identifier: 10.1109/ICSPCS.2010.5709687*

Lili Cao; Haitao Zheng (2008) *“Distributed Rule-Regulated Spectrum Sharing”, IEEE Journal on Selected Areas in Communications, 2008*

M.A. McHenry, (2005) “NSF Spectrum Occupancy Measurements Project Summary,” *Technical Report, Shared Spectrum Company*

M.A. McHenry, P.A. Tenhula, D. McCloskey, D.A. Roberson, and C.S. Hood (2006) “Chicago Spectrum Occupancy Measurements & Analysis and a Long-Term Studies Proposal,” Proc. *First Int’l Workshop Technology and Policy for Accessing Spectrum*

Magnús M. Halldórsson ; Pradipta Mitra (2012) “Wireless Capacity and Admission Control in Cognitive Radio”, *INFOCOM, Proceedings IEEE*

Mingrui Zou, Chengshi Zhao, Bin Shen, Kyungsup Kwak (2008) “Comparison of DF and AF based Cooperative Spectrum Sensing in Cognitive Radio Communications”, *APCC. 14th Asia-Pacific Conference*

Mingrui Zou; Chengshi Zhao; Bin Shen; Kyungsup Kwak, (2008) “An Adaptive Threshold Based Energy Detector for Spectrum Sensing in Cognitive Radios at Low SNR Decode-and-Forward Protocol Based Cooperative Spectrum Sensing in Cognitive Radio “; *Convergence and Hybrid Information Technology, ICCIT '08. Third International Conference*

Mingrui Zou; Chengshi Zhao; Bin Shen; Kyungsup Kwak (2008) “Comparison of DF and AF Based Cooperative Spectrum Sensing in Cognitive Radio “, *Communications,. APCC 14th Asia-Pacific Conference*

Myung Sung Jang; Dong Jun Lee (2009) “Optimum Sensing Time Considering False Alarm in Cognitive Radio Networks”, Personal, *Indoor and Mobile Radio*

Communications, IEEE 20th International Symposium on Digital Object Identifier: 10.1109/PIMRC.2009.5450020

O. Simeone; I. Stanojev ; S. Savazzi ; Y. Bar-Ness ; U. Spagnolini ; R. Pickholtz (2008) "Spectrum Leasing to Cooperating Secondary Adhoc Networks*", IEEE Journal on Selected Areas in Communications*

Peyman Setoodeh; Simon Haykin (2017), "Fundamentals of Cognitive Radio", *Print ISBN:9781118302965, John Wiley & Sons*

Qi Qu ; Laurence B. Milstein ; Dhadesugoor R. Vaman, (2008) "Cognitive Radio Based Multi-User Resource Allocation in Mobile Ad Hoc Networks Using Multi-Carrier CDMA Modulation" *IEEE Journal on Selected Areas in Communications*

Qiang Wu, Yiming Ying, Ding-Xuan Zhou (2004) ": Support Vector Machine Soft Margin Classifiers: Error Analysis", *Journal of Machine Learning Research*

R. Ananthapadmanabha, B. S. Manoj, and C. Siva Ram Murthy (2001) "Multi-Hop Cellular Networks: The Architecture and Routing Protocol," *Proceedings of IEEE PIMRC*

R. Chandramouli, Ananthram Swami, John Chapin and K. P. Subbalakshmi (2010) "Dynamic Spectrum Access for Wireless Networking", *EURASIP Journal on Advances in Signal Processing 2010 2009:630912*

R. S. Blum, S. A. Kassam, and H. V. Poor (1997) "Distributed Detection with Multiple Sensors: Part II - Advanced Topics," *Proc. IEEE, Vol. 85, No. 1, pp. 64–79*

R. Tandra, S. M. Mishra, and A. Sanai (2009) "What is a Spectrum Hole and What Does it Take to Recognize One?" *Proceedings of the IEEE, Volume: 97*

Rahul Singh Sarita Kansal (2016) "Performance evaluation of neural network based spectrum sensing in cognitive radio", *Internet of Things and Applications (IOTA), IEEE Proceedings , 22-24 Jan. 2016*

Ranganathan, P.; Ranganathan, A.; Minai, A.; Berman, K. (2006) “A Self-Organizing Heuristic for Building Optimal Heterogeneous Ad-Hoc Sensor Networks”, *Networking, Sensing and Control, Proceedings of the IEEE International Conference*

Ranganathan, P.; Ranganathan, A.; Minai, A.; Berman, K. (2006) “A Self-Organizing Heuristic for Building Optimal Heterogeneous Ad-Hoc Sensor Networks “, *Networking, Sensing and Control, ICNSC '06*

Renchao Xie; Yu, F.R.; Hong Ji, (2012) “Energy-Efficient Spectrum Sharing and Power Allocation in Cognitive Radio Femto Cell Networks”, *INFOCOM, 2012 Proceedings IEEE*

Rong Cong; Zhen Yang (2010) “Optimization of Out-Band Sensing Time in Cognitive Radios”, *Progress in Informatics and Computing (PIC), IEEE International Conference*

S. Haykin, (2006) “Cognitive Dynamic Systems,” *Proc. IEEE, Vol. 94, pp. 1910–1911*

S. Haykin (2005) “Cognitive Radio: Brain-Empowered Wireless Communications,” *IEEE J. Select. Areas Commun., Vol. 23, No. 2, pp. 201–220*

Salma Bourbia ; Madiha Achouri ; Khaled Grati ; Daniel Le Guennec ; Adel Ghazel, (2012) “Cognitive Engine Design for Cognitive Radio”, *Multimedia Computing and Systems (ICMCS), International Conference*

Scc41 (2005), http://www.scc41.org/ http://grouper.ieee.org/groups/802/22

Scikit (2010), *scikit-learn.org*

Serrador, A.; Correia, L.M. (2008) “A Model for Heterogeneous Networks Management and Performance Evaluation”, Network *Operations and Management Symposium, NOMS*

Serrador, A.; Correia, L.M. (2008) “A Model for Heterogeneous Networks Management and Performance Evaluation”, *Inst. Super. de Eng. de Lisboa, Polytech. Inst. of Lisbon, Lisbon*

SiXing Yin; Dawei Chen; Qian Zhang; Mingyan Liu; ShuFang Li: (2012) "Mining Spectrum Usage Data: A Large-Scale Spectrum Measurement Study" *Mobile computing, Volume: 11, Issue: 6*

Stefan Geirhofer; Lang Tong; Brian M. Sadler (2008) "Cognitive Medium Access: Constraining Interference Based on Experimental Models" *IEEE Journal on Selected Areas in Communications*

Steven M. Kay (1998) "Fundamentals of Statistical Signal Processing - Part I and II", *Prentice Hall Publication*

Stotas, S.; Nallanathan, A. (2011) "Optimal Sensing Time and Power Allocation in Multiband Cognitive Radio Networks Communications", *IEEE Transactions on Communications*

Stotas, S.; Nallanathan, A. (2010) "Sensing Time and Power Allocation Optimization in Wideband Cognitive Radio Networks", *GLOBECOM, IEEE Global T*elecommunications *Conference*

SVM (2013), Wikipedia, https://en.wikipedia.org/wiki/Support_vector_machine,

T. Hastie, R. Tibshirani and J. H. Friedman (2009) "Elements of Statistical Learning" , *Springer Series in Statistics, Data Mining, Inference, and Prediction, Second Edition, ISBN 978-0-387-84858-7,2009*

Tang, Long Chi, He-hua Wu, Jue-bo (2010) "Study on Heterogeneous Networks Integration based on Cognitive Wireless Network", *Computational Intelligence and Software Engineering (CiSE)*

Theodore S. Rappaport (1996), "Wireless Communications Principles and Practice" *Second Edition, Pearson Publications*

Tianlong Yu, Vyas Sekar, Srinivasan Seshan, Yuvraj Agarwal, Chenren Xu, (2015) "Handling a Trillion (Unfixable) Flaws on a Billion Devices: Rethinking Network Security for the Internet-of-Things"

Tingting Liu; Jianxin Wang; Feng Shu (2010) “Optimal Sensing Time Based on the Target Function in Cognitive Spectrum Sensing”, *Future Computer and Communication (ICFCC), 2nd International Conference*

Vinko Erceg, Larry J. Greenstein, Sony Y. Tjandra, Seth R. Parkoff, Ajay Gupta, Boris Kulic, Arthur A. Julius, and Renee Bianchi (1999) “An Empirically Based Path Loss Model for Wireless Channels in Suburban Environments”, *IEEE Journal on Selected Areas in Communications, Vol. 17, No. 7*

Volodymyr Mnih, Koray Kavukcuoglu, David Silver, Andrei A. Rusu, Joel Veness, Marc G. Bellemare, Alex Graves, Martin Riedmiller, Andreas K. Fidjeland, Georg Ostrovski, Stig Petersen, Charles Beattie, Amir Sadik, Ioannis Antonoglou, Helen King, Dharshan Kumaran, Daan Wierstra, Shane Legg, Demis Hassabis, (2015) “Human-Level Control Through Deep Reinforcement Learning”, *Nature 518, 529–533, doi:10.1038/nature14236*

Wei Zhang, Ranjan K. Mallik, Khaled Ben Letaief, (2009) “Optimization of Cooperative Spectrum Sensing with Energy Detection in Cognitive Radio Networks”, *IEEE Transactions on Wireless Communications*

Wei Zhang; Mallik, R.K.; Ben Letaief, K, (2008) “Cooperative Spectrum Sensing Optimization in Cognitive Radio Networks”, *Communications, ICC '08. IEEE International Conference*

Wellens, M.; Riihijarvi, J.; Gordziel, M.; Mahonen, P (2009) “Spatial Statistics of Spectrum Usage: From Measurements to Spectrum Models” Communications*, ICC '09*

Xu Dong; Ying Li; Chun Wu; Yueming Cai (2010) “A Learner Based on Neural Network for Cognitive Radio” , *Communication Technology (ICCT), 12th IEEE International Conference*

Xuebing Pei; Tao Jiang; Daiming Qu; Guangxi Zhu; Jian Liu (2010) “Radio-Resource Management and Access-Control Mechanism Based on a Novel Economic Model in Heterogeneous Wireless Networks”, *IEEE Transactions on Vehicular Technology*

Xuebing Pei; Tao Jiang; Daiming Qu; Guangxi Zhu; Jian Liu (2010) “Radio-Resource Management and Access-Control Mechanism Based on a Novel Economic Model in

Heterogeneous Wireless Networks", *IEEE Transactions on Vehicular Technology, Volume: 59, Issue: 6*

Y. H. Zeng and Y. C. Liang (2009) "Eigenvalue Based Sensing Algorithms for Cognitive Radio", *IEEE Trans. Commun., Vol. 57, No. 6, pp. 1784–1793*

Y. Hur; J. Park; W. Woo; J. S. Lee; K. Lim ; C. H. Lee ; H. S. Kim ; Joy Laskar (2006) " WLC05-1: A Cognitive Radio (CR) System Employing A Dual-Stage Spectrum Sensing Technique: A Multi-Resolution Spectrum Sensing (MRSS) and A Temporal Signature Detection (TSD) Technique", *Global Telecommunications Conference, GLOBECOM '06*

Y. Thomas Hou ; Yi Shi ; Hanif D. Sherali (2008) " Spectrum Sharing for Multi-Hop Networking with Cognitive Radios", *IEEE Journal on Selected Areas in Communications*

Y.D. Lin and Y.C. Hsu (2000) "Multi-Hop Cellular: A New Architecture for Wireless Communications," Proceedings of IEEE INFORCOMM

Yannan Yuan; Yuliang Tang; Congren Lin (2010) "A Novel Mobility Prediction Mechanism in Heterogeneous Networks", *Communications and Mobile Computing (CMC), International Conference*

Yannan Yuan; Yuliang Tang; Congren Lin (2010) "A Novel Mobility Prediction Mechanism in Heterogeneous Networks*", Communications and Mobile Computing (CMC)*

Ying-chang Liang; Hsiao-hwa Chen ; Joseph Mitola ; Petri Mahonen ; Ryuji Kohno ; Jeffrey H. Reed ; Larry Milstein (2009) ,"Guest Editorial - Cognitive Radio: Theory and Application" *Proceedings of the IEEE, Special Issue on "Cognitive Radio - I", Vol. 97, No. 4*

Yiyang Pei; Ying-Chang Liang; Kah Teh; Kwok Li (2009) "How Much Time is Needed for Wideband Spectrum Sensing?", *Wireless Communications, IEEE Transactions on Volume: 8, Issue: 11 Digital Object Identifier: 10.1109/TWC.2009.090350*

Yu, F.R.; Minyi Huang; Tang, H (2010)" Biologically Inspired Consensus-Based Spectrum Sensing in Mobile Ad Hoc Networks with Cognitive Radios Network", *IEEE Volume: 24*

Yucek, T., Arslan, H. (2009) “A Survey of Spectrum Sensing Algorithms for Cognitive Radio Applications” Communications *Surveys & Tutorials, IEEE Volume: 11 Issue:1*

Zhang Jin-bao; Chen Xia; Tang Rui (2007) “A Novel Mobility Management Scheme for Convergence of Heterogeneous Networks” *Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications*

Zhenghao Zhang ; Husheng Li ; Changxing Pei (2010), “Optimum experimental design for estimating spatial variogram in cognitive radio networks” *Information Sciences and Systems (CISS), 2010 44th Annual Conference*

Zhi Quan; Shuguang Cui; Sayed, A.H. (2007) “An Optimal Strategy for Cooperative Spectrum Sensing in Cognitive Radio Networks”, *Global Telecommunications Conference, GLOBECOM '07*

*Zhu Ji; K. J. Ray Liu (2008) “*Multi-Stage Pricing Game for Collusion-Resistant Dynamic Spectrum Allocation”, *IEEE Journal on Selected Areas in Communications*

APPENDIX -1

Research publications associated with the thesis

Sl. No	Title	Journal / Conference details
1	**Co-operative Spectrum sensing using CR node binary decision regression on estimated wireless path-loss curves**	ICECS-2014, IEEE Conference Paper
2	**3D Spectrum hole detector using Support Vector Machine to enable D2D overlay on the heterogeneous CR network**	ICEDS-2017, IEEE Conference Paper