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This work and its defense approved by:

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Enhancing Wireless Mesh Network Performance using Cognitive Radio with Smart Antennas

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ABSTRACT

Wireless Mesh Networks (WMNs) are believed to revolutionize wireless internet connectivity by economically extending broadband internet over very large areas. In their default state, WMNs operate in the ISM band. Due to severe congestion in this unlicensed band, some of the constituent Mesh Routers (MRs) in a WMN may have over-congested operating conditions. Hence, it is desirable for such MRs to operate on a different band. There exist unused or white spaces in the spectrum used by licensed operators, who are referred to as Primary Users (PUs). Cognitive radio technology is one that can enable MRs in a WMN with poor channel conditions to shift operation to this licensed spectrum. This opportunistic sharing of the white spaces in the licensed spectrum results in higher spectral efficiency as well as reduced traffic volume in the ISM band. Most recent research only considers using omni-directional antenna at each Mesh Client (MC). This is inefficient, especially in the case of a Cognitive WMN (CWMN) as it shifts the operation of an entire cluster of nodes to the primary band and could induce inadmissible interference on the PUs. Our proposed architectural design employs spatial selectivity through smart antennas, encourages load sharing among the numerous MRs in the ISM band, as well as increases throughput with efficient spectrum utilization. We study the interference reduction at the PUs, considering a CWMN with smart antennas embedded in each MC. We compare the scenarios with MCs in a WMN equipped with omni-directional, directional, and smart antennas through extensive simulations and determine their effect on interference caused to the PUs. To reduce interference levels at the PUs further, we propose techniques to regulate the transmission powers of the MCs. Finally, we propose models that significantly improve the spectrum sensing mechanism of a CWMN, through analysis of historical data of PU behavior in accessing the spectrum.

To my loving parents and wonderful brother,
who have made me everything I am.

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Chapter 1

1. Introduction

1.1 Wireless Mesh Networks

Wireless Mesh Network (WMN) is a technology that is rapidly gaining increased interest for its ability to usher in cheap extendable wireless internet connectivity for mobile users. They are designed primarily using many of the same operating principles as that of Wireless Mobile Ad-hoc Networks (MANETs) [1][2]. However, the focus of WMNs is more on extending internet connectivity throughout the entire network, as opposed to peer to peer connectivity in the case of MANETs. Hence, their structure is more centralized to facilitate this.

The primary advantage of implementing WMNs lies in the fact that wired broadband internet connectivity has to be established only in a few terminals, as compared to Wireless Local Area Network (WLAN). In the case of WLAN, every mobile user gains internet connectivity through a wireless connection to an access point (AP). Each AP is required to have a wired connection to the internet. In the case of a WMN, there exist terminals called Internet Gateways (IGWs). These terminals also serve as MRs and are the only ones that require wired connection to the internet. There are far fewer IGWs in a WMN than APs in a WLAN of comparable size. Hence, the constriction of having wired ports is far limited in WMNs. The internet connection established at the IGWs is extended throughout the WMN through mesh routers (MRs).

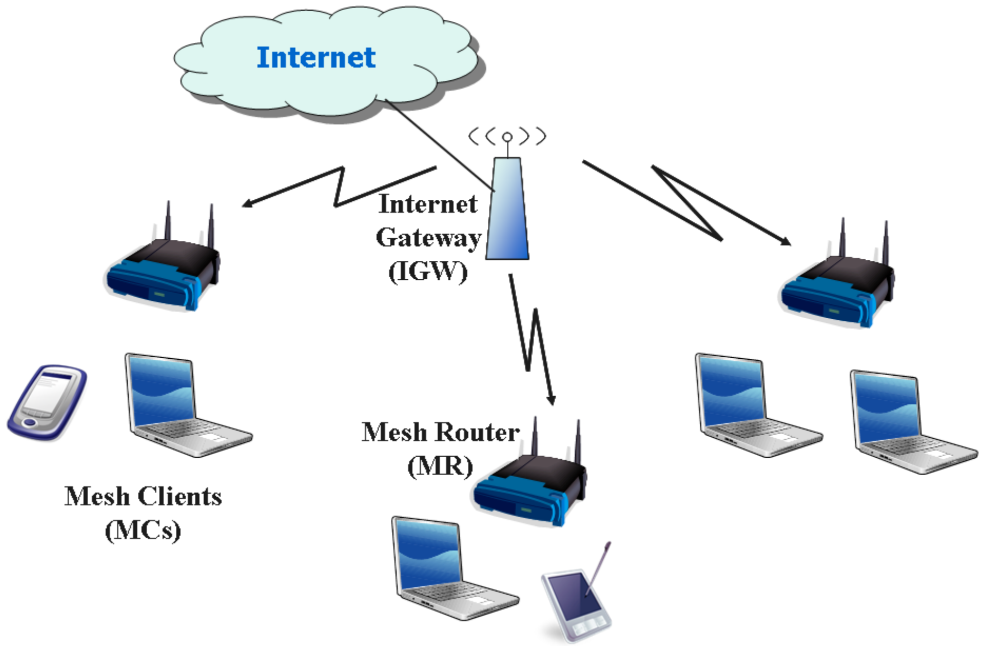


Figure 1.1 - Illustration of a Wireless Mesh Network

Figure 1.1 shows the structure of a typical WMN, with only one IGW, which has a wired connection to the internet. There exist multiple MRs which connect wirelessly to the IGW. The MRs form a wireless backhaul network through which broadband internet access is extended wirelessly throughout the network. The wireless users served by an MR are referred to as Mesh Clients (MCs). An MR along with its associated MCs is referred to as a mesh cluster. The WMN succeeds in providing good data rates to the MCs with acceptable Quality of Service (QoS) conditions. Another key advantage of a WMN is its capability of being dynamically extended by deploying more MRs. A new MR may dynamically connect to an IGW, or just any MR in the existing WMN to serve MCs of its cluster and extend internet access to them. When any MR is simply plugged and turned on, active MRs automatically reconfigure their connections so as to add new MR to the network.

A WLAN provides high data rate connectivity with the limitation of requiring multiple wired connections at APs. A cellular network does cover a significantly larger range, but the data rates offered are much lower than WLAN connectivity. The WMN succeeds in providing the best of both worlds by its ability to provide extendable high data rate connectivity over a larger range than other competing technologies such as WLAN.

The WMN operates in the unlicensed ISM band, which is subject to a lot of congestion and interference. Our research work deals with implementing CR technology to a WMN to relieve aversely affected MRs, by shifting its frequency of communication with all its associated MCs, to that of a PU. Such shift in frequency calls for ensuring minimum interference caused to the PUs. In a typical CR network, only one pair of SU transmitter and receiver shifts operating frequency to the PU band. However, our system must handle interference resulting from an entire mesh cluster of SUs shifting operating frequency. To deal with the especially large amount of interference, we propose to improve the efficiency in transmission using spatial selectivity through smart antennas.

1.2 Motivation for our work

A WMN is envisioned to provide internet access over a very large area. Multiple factors such as node densities, interference between neighboring wireless devices and the deployment structures of different sections in the area are bound to vary. Hence, it is to be expected that each of these different sections would experience different interference conditions. From the theoretical and simulation results performed in [3], it is seen that the throughput per node in a

WMN decreases drastically if the density of MCs is increased. Stagnation in observed throughput per node can also be noticed with increased load. Different MCs may also have varied bandwidth requirements. Furthermore, the entire WMN is set to operate on the unlicensed 2.4 GHz ISM band, which is also shared by other popular networking architectures such as WLAN and Bluetooth. This congestion contributes interference to the WMN in areas where such technologies are deployed in its close vicinity. Due to multitude of such factors, it is expected that some MRs suffer from poor channel conditions in their default state and would be incapable of providing acceptable service to its associated MCs.

Hence, we are motivated to free those MRs experiencing such poor channel conditions by moving them out of their default band of operation to a different frequency band. Cognitive Radio (CR) Technology [4][5][6] enables a device to identify unused portions of licensed spectrum and shift its operating frequency to that spectrum. Such a shift to an unused frequency band could improve the performance of an MR and its service to its constituent MCs. It would also reduce existing load in the default band in which the remaining MRs of the WMN operate. Hence, this research work deals with imparting CR capabilities to a WMN in order to improve performance of the MRs facing poor channel conditions, with major focus on ensuring operable channel conditions and reducing interference caused to the licensed Primary Users (PUs).

1.3 Related Work

Cognitive radio seems to be a potential candidate in WMNs and facilitate efficient channel allocation and better communication among MRs and SUs as Mesh Clients (MCs). Chen et al. [7] have proposed methods for formation of clusters among MCs and present methods of sharing information over multiple channels. The authors utilized the approach of open spectrum sharing in doing an efficient channel assignment and adaptation to varying network configurations. Chowdhury et al. [8] presented an interference model in CWMNs, with an idea of load balancing among MRs by switching specific transmissions from Industrial, Science, and Medical (ISM) band (2.4GHz) to licensed television bands. The authors assumed omni-directional transmissions for such interference studies.

Spatial diversity is assumed in several research works that improve co-existence of PUs and SUs, resulting in higher spectrum utilization. Zhang et al. [9] considered joint beamforming and power allocations among the SUs, while using spatial diversity like Single Input Multiple Output (SIMO) systems. Islam et al. [10] discussed cooperative communications among the PUs and SUs for efficient spectrum usage using joint beamforming and power allocations for downlink communication. Later on, Islam et al. [11] also developed a beam synthesis technique to update the beamforming weights and replicate spatial and temporal properties of spectrum occupancy for PUs in the television bands. Spatial selectivity in the form of smart antenna has shown definite advantages in the cognitive radio domain. Huang et al. [12] presented the idea of co-existence of the PUs and SUs. The authors have also proved that the implementation of smart antenna on both the PUs and SUs can yield better spectral usage and co-existence possible while mitigating the interference to the PUs.

Since interference power is critical in cognitive radio networks for possible co-existence with PUs, reduction of interference study in CWMNs draws special attention. To the best of our knowledge, such work has never been pursued in the cognitive radio parlance. This critical concern of interference reduction in CWMNs is the central idea of our research work while we also focus on load balancing in existing ISM band communication to tackle bottleneck problems.

1.4 Thesis Organization

Figure 1.2 shows how the remainder of the thesis is organized. Chapter 2 provides the necessary background information regarding the key elements in this work, namely CR Technology and Smart Antennas. The primary focus of this research work is to ensure that interference levels at the PUs are kept within specified limits, while enabling operation of the WMN in the PU environment. Smart Antennas are key to reducing the interference levels at the PUs through spatial selectivity. The chosen technique of Smart Antenna operation and its implementation in simulation are elaborated in Chapter 2.

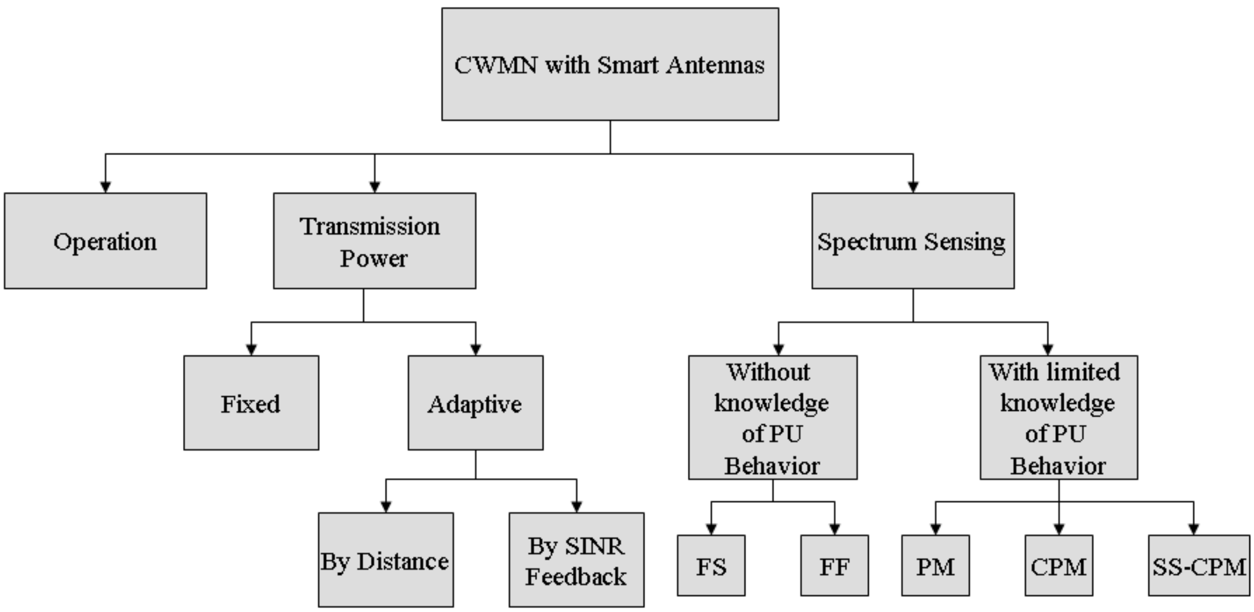


Figure 1.2 - Thesis Organization

Chapter 3 describes the system setup of a Cognitive Wireless Mesh Network (CWMN) and the approach implemented to achieve spectral efficiency. The load balancing algorithm that governs how an MR facing poor channel conditions, decides to shift its operating frequency to the PU's band is elucidated. The mechanisms by which it operates in the new band are described in detail. Spatial selectivity is implemented using smart antennas and the improvements achieved are studied. Aiming to ensure operable conditions at the PUs, their Signal to Interference-Noise Ratio (SINR) performance is evaluated.

Chapter 4 aims to further improve the SINR performance of the PUs by regulating the transmission powers of the MCs. The default operation is based on static (fixed) transmission powers of the MCs. Two techniques to improve PU SINR performance by adaptive transmission powers of the MCs are proposed and evaluated. The first technique involves regulating the transmission power depending on the distance from the intended receiver. The second technique aims at realizing just enough transmission power levels to achieve a required SINR at the MCs and is done in a more efficient manner through SINR feedback from the intended receiver.

The focus of Chapter 5 is to improve the efficiency of the Spectrum Sensing mechanism of the system, which is an integral part of the Cognitive operation in detecting an unoccupied portion of the spectrum. The default mode of operation involves scanning every available sub-band licensed to the PU. Several techniques are proposed to reduce the number of power measurements required to find an available sub-band and the conditions change from having no knowledge to limited knowledge of PU behavior in the sub-bands.

Chapter 6 finally provides a summary and conclusion to the work presented. It also lists areas in which future work may be pursued.

Chapter 2

2. Background

2.1 Introduction

The major topics involved in this thesis work are Cognitive Radio Technology and Smart antennas. This chapter aims at providing background information on the salient features of these technologies which are relevant to our work. The implementations of smart antennas are quite varied, and hence the specific implementation used in this work is particularly discussed in detail.

2.2 Cognitive Radio Technology

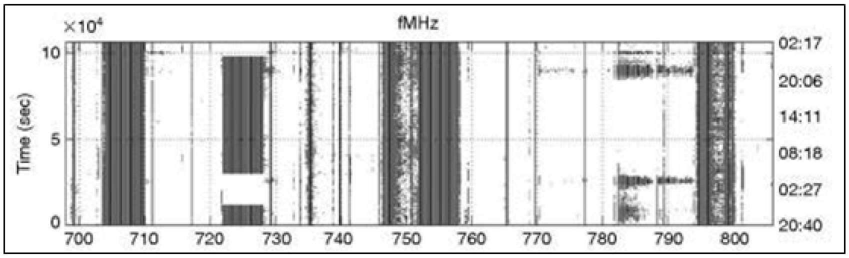
The wireless communication technology has improved at a very rapid pace ever since the cell phones became popular. Recent advances have enabled much faster data transfer rates and hence ushered in data centric services such as internet access, data and multimedia transfer, gaming and high speed audio and video transmissions. Studies estimate that the data transfer rate requirements from these wireless communication technologies will continue to grow at an exponential rate. Increased data rate requirements have been handled by primarily allocating more frequency bands to the service providers. For increasing acceptability of data communication, it has almost come to the point where all significant portions of the available spectrum have already been allocated to licensed users. As a result, blindly allocating frequency bands to ubiquitous growth of the need for resources is not an efficient solution. Another possibility of improving the data communication throughput is to enhance the modulation and encoding of the communication standard used. However, existing schemes are considered to have been optimized as much as possible. Further improvement, though not ruled impossible, is most likely to have just a marginal increase and may not commensurate with an expected bandwidth requirement.

2.2.1 The Proposed Solution of Unlicensed Spectrum Access

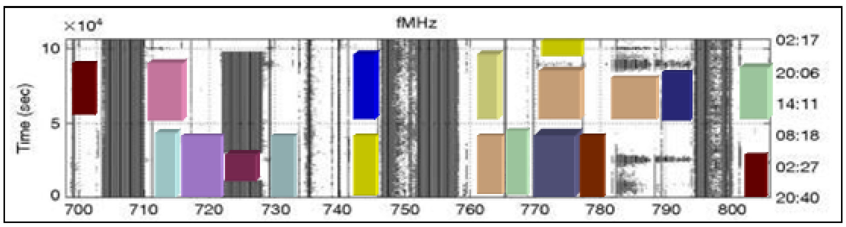
Any expected solution to the rapidly increasing spectrum requirement could be a drastically different approach in accessing the spectrum itself. The Federal Communications Commission (FCC) initiated studies on the band usage of the spectrum that has been licensed to operators, who are referred to as Primary Users (PUs). Some explicit observations made by them are [4]:

- Some frequency bands are largely unoccupied for most of the time,
- Some frequency bands are only partially occupied and
- The remaining bands are heavily used.

Observing such under-utilization of spectral resources, FCC recommends that significantly better bandwidth utilization may be achieved by deploying wireless devices that can co-exist with the licensed PUs. It proposes allowing unlicensed users to temporarily borrow spectrum from the PUs, when it is not being utilized. The major steps to be carried out by the unlicensed users are spectrum sensing, to detect unused bands, and then shifting operating frequency to that band. Cognitive Radio (CR) Networks are means to implement such a strategy of dynamic spectrum access.



(a)



(b)

Figure 2.1 - Opportunistic Spectrum Sharing
(a) Spectrum utilization over a period of 18 hours performed in New Jersey [13]
(b) Opportunistic spectrum sharing of TV bands utilizing the spectrum holes [6]

Figure 2.1 (a) shows a study of the spectrum utilization in the TV band (700 to 820 MHz) in New Jersey [13], performed over 18 hours. The gray portions represent utilization of the spectrum by the PUs and the white portions are the unused sections of the spectrum, referred to as white spaces. This experiment verifies the observations stated by the FCC that a large portion of the licensed spectrum is under-utilized. These white spaces provide opportunities for spectrum sharing. Figure 2.1 (b) shows how the spectrum could be shared with a set of secondary users (SUs) [6]. Each colored block represents an SU, which opportunistically shares the licensed spectrum with the PUs through a defined protocol. Such a mechanism could benefit both the sets of users. Based on the policies agreed upon, depending upon the duration and frequency range of SU usage, the PUs may receive monetary benefits from the SUs, while SUs can access the spectrum at lower costs and transmit using a higher bandwidth.

2.2.2 Operation Constraints

Permitting such access of the spectral resources to SUs is clearly unreasonable to the PUs. Hence, priorities are to be given to PUs. An SU may use only the frequency band that is currently unoccupied by any of the PUs. If a PU requires access of the frequency band in the middle of a communication by the SU in that band, preference must be given to the PU and the SU must move over and use a different frequency band, or it may stay in the same band after altering its transmission power level or its modulation scheme so as not to cause any visible interference to the PU. Other harsher constraints on the SUs are that no additional interference be imposed on the PU and that the primary encoder-decoder pair should be completely oblivious to the presence of the CR enabled users. In this thesis, we consider the CR technology in a Wireless Mesh Network setup.

2.3 Smart Antennas

Spatial selectivity refers to a form of directional transmission, as opposed to an omni-directional case. Instead of transmitting in all directions with the same intensity, transmission is focused to a portion of space, selected as per requirements. This requirement typically involves restricting transmissions to the direction in which the intended receiver is located. In our case, it also involves selecting the spatial segment of transmission so as to avoid causing interference to PUs.

2.3.1 Inefficiency of omni-directional antennas

Due to cost-effectiveness and ease of implementation, omni-directional antennas are used as the industrial standard in wireless devices. They operate by radiating power in all directions. In most practical instances, the radiation patterns are not exactly uniform for these antennae, but our implementations approximate that the radiations are uniform in all directions.

Our work largely deals with the co-existence of a WMN with PUs in the licensed spectrum. Hence, the following scenarios are shown with reference to such a system.

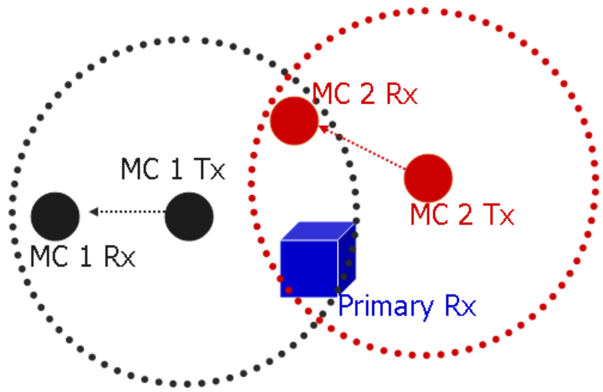


Figure 2.2 - Depiction of Omni-directional Transmissions

Figure 2.2 shows two MC pairs communicating using omni-directional antennas. The dotted circles around the MC transmitters represent their transmission range. As explained, the radiation pattern is circular, assuming uniform radiation in all directions. The MC pairs are operating in the vicinity of a PU receiver. Our work concentrates on reducing the interference caused by the MC nodes to such PU nodes. As seen in the above scenario, interference at the PU receiver is caused by both the MC transmitters in its vicinity. Essentially, it is seen that these antennas cause unwanted radiations in directions other than those of interest. Hence, the omni-directional antennas incorporated into the MCs are inefficient forms of transmission for our system.

2.3.2 Spatial Selectivity

Spatial selectivity is a widely used method in reducing active interference. It involves concentrating the radiated power in certain desired directions. This helps to reduce interference caused to other nodes. It also minimizes the power required for transmissions, since there is much less power wasted in unwanted directions. Thus, the inefficiency of omni-directional antennas can be overcome using spatial selectivity, which is achieved through the use of directional antennas. Figure 2.3 shows how the system overcomes the inefficiency portrayed in Figure 2.2 using directional antennas.

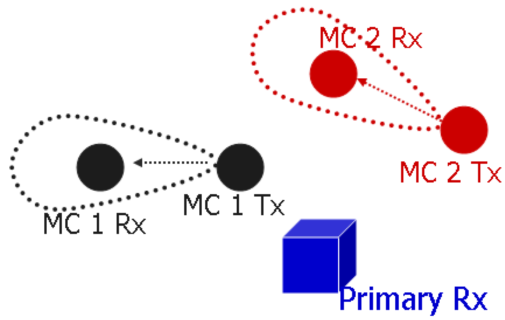


Figure 2.3 - Depiction of Directional Transmissions

When the MC transmitters incorporate directional antennas, they are capable of steering the radiating beam in the direction of the intended receiver. By doing so, radiation in unwanted directions can be eliminated. Thus, observed interference caused by directional antennas to the PU receiver is much smaller as compared to omni-directional antennas.

Figure 2.3 represents the ideal case of a directional antenna. The beam pattern of a practical directional antenna is shown in Figure 2.4. Most of the radiated power is concentrated in the required direction. The transmission lobe formed in this direction is called the main lobe. The ideal transmission illustrated in Figure 2.3 involves only the main lobe. However, practical antennas are not that perfect. They induce transmissions in directions other than that in consideration, though not as large. These are known as side lobes. The spaces between lobes are the points of near zero transmissions, referred to as nulls.

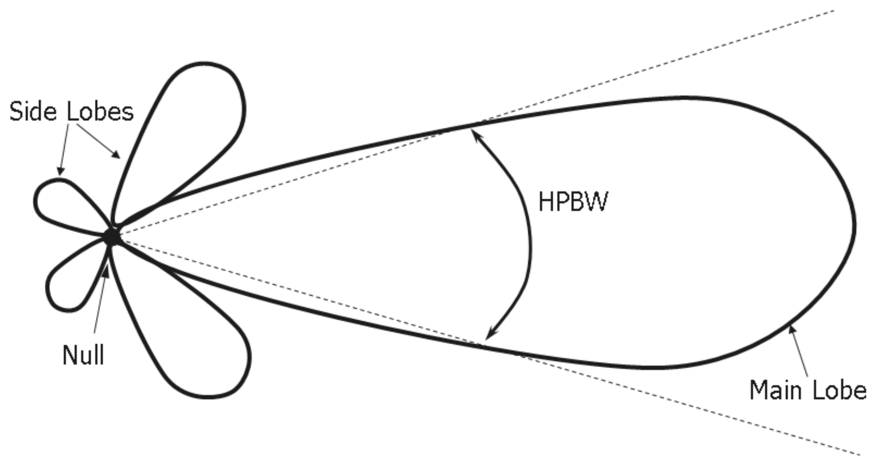


Figure 2.4 - Directional Antenna Beam

A commonly used measure of the directionality of an antenna is the Half Power Beamwidth (HPBW). It represents the efficiency of an antenna in restricting its transmission. It is the angle between the points of the main lobe where the radiation intensity is half of its maximum.

Figure 2.5 (a) shows the impact of the side lobes in the example in consideration when directional antennas are used. Due to the presence of side lobes from the MC transmissions, the PU receivers still experience interference from the MCs. Hence, directional transmissions cannot perfectly avoid interference to other users due to the side lobes.

Figure 2.5 (b) shows the construction of a simple form of a directional antenna. It consists of an array of antenna elements. Varying the excitation to each element causes the radiation beam pattern of the antenna to change. By a central control of the magnitude and phase excitations to each of the inputs, a desired beam direction can be obtained. Figure 2.5 (b) illustrates each of the antenna elements being of equal length and all elements placed with equal spacing. These are parameters used in the design of different types of directional antennas such as the Yagi-Uda, Log Periodic antennas and corner reflectors. Each type is constructed on different design considerations and finds applications in different scenarios.

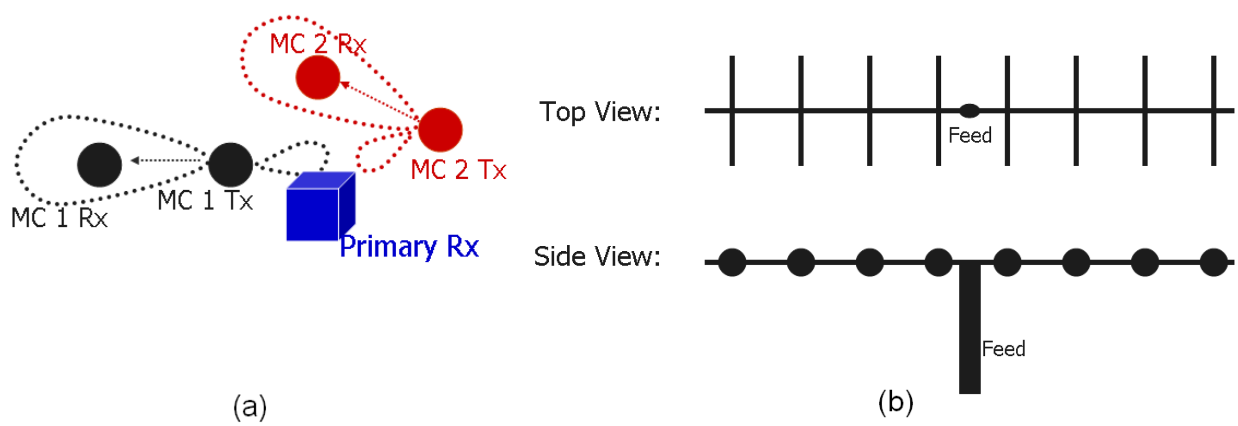


Figure 2.5 – Directional Antennas
(a) Scenarios defining imperfections
(b) Antenna array design

2.3.3 Overcoming the drawbacks of directional antennas

The static nature of the side lobes in transmission is the major drawback of directional antennas. Though it is not possible to completely suppress the side lobes, it is possible to control the position of the side lobes, and hence the nulls formed by them. Thus, the most efficient way of data transmission with respect to our system considerations would be to steer the side lobes, so that nulls are formed in the direction of the PU receivers. This is shown in Figure 2.6, where the MC transmitters steer their side lobes away from the PU receiver, while at the same time, directing their main lobe towards their intended receivers.

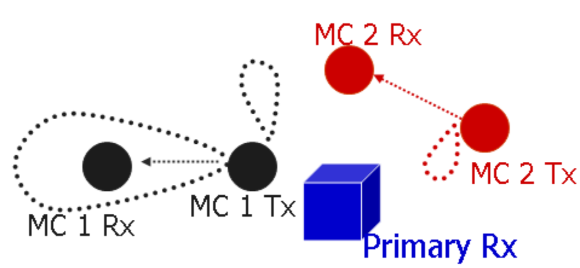


Figure 2.6 - Steering side lobes

Such efficient transmissions with reduced interference can be achieved using Smart antennas. They are capable of directing transmissions in the intended direction as well as steering side lobes in a way to form nulls in desired directions. Hence, by avoiding transmissions in undesired directions, they satisfy the requirement of bringing the total interference experienced by the PUs to a minimum.

2.3.4 Blocks of a Smart Antenna

Figure 2.7 shows the blocks of a smart antenna with R antenna array elements, denoted as x_1 to x_R. The vector weights given as inputs to each antenna element are represented as w_1 to w_R. The weights are varied in both magnitude and phase, causing phase manipulations in generated signals so that a desired beam pattern is formed.

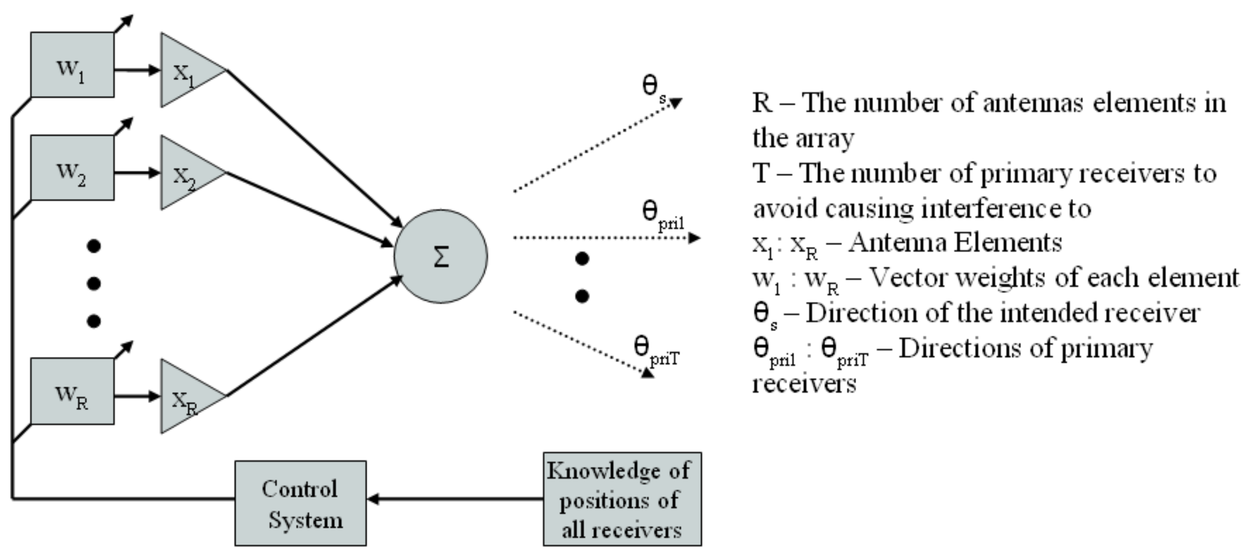


Figure 2.7 - Blocks of a smart antenna

This scenario shows θ_s as the direction of the intended receiver. Varying the inputs allow steering the main lobe in the required direction. Figure 2.7 considers the presence of T PU receivers, located at directions θ_{pri1} to θ_{priT}. By providing appropriate inputs to the antenna elements, nulls may be positioned in the direction of the PU receivers so as to avoid causing interference to them. This is achieved through a central control system that operates with the knowledge of θ_s and all θ_{pri}. It calculates the optimal weights, which would generate a beam pattern to satisfy the requirements from the main lobe and side lobes.

There are different ways by which the optimal weights can be calculated to form the required beam pattern, such as the maximum signal to interference Ratio (SIR) technique, Minimum Mean Squared Error (MMSE) technique, maximum likelihood technique and minimum variance technique [14]. Our work requires both positioning nulls in the direction of the PU receivers as well as concentrating most of the power in the direction of the intended MC receiver. The MMSE technique proves to be most effective and is adopted in our work.

2.3.5 Minimum MSE Technique [14]

As the name suggests, this technique operates with the aim of minimizing the MSE between the beampattern achieved and the ideal beampattern of the system. Hence, it aims to find the optimal set of antenna element weights that maximizes the correlation between the generated beam pattern and the desired beam pattern. The desired beam pattern corresponds to the required null formations for PUs and the main lobe direction for the intended SU MC receiver.

For an MC transmitter array with R elements, inter-element spacing d, T PU receivers and angle of alignment of the desired MC receiver, θ_s, the transmit angle steering vector is derived as:

$$\overline{x_s} = [e^{-jkd*sin(\theta s)*ceil(R/2)} \; e^{-jkd*sin(\theta s)*ceil(R/2)-1} \; \ldots \; e^{jkd*sin(\theta s)*ceil(R/2)}]^T. \quad (2.1)$$

The PU receiver positions, with respect to the MC transmitter, are expressed as θ_i, where $i \in [1,2,\ldots T]$. The required nulls steering vectors, $\overline{n_i}$ (in this case, for each PU receiver) is calculated by using the following equation (2.2), one vector per PU receiver angle:

$$\overline{n_i} = [e^{-jkd*sin(\theta i)*ceil(R/2)} \; e^{-jkd*sin(\theta i)*ceil(R/2)-1} \; \ldots \; e^{jkd*sin(\theta i)*ceil(R/2)}]^T. \quad (2.2)$$

The entire matrix of steering vectors is given as:

$$A = [n_1\ n_2\ \ldots\ n_T]. \tag{2.3}$$

The signal and interference correlation matrices, $\overline{R_{ss}}$ and $\overline{R_{ii}}$ respectively, are calculated as:

$$\overline{R_{ss}} = E[\overline{x_s}\ \overline{x_s}^H], \text{ and} \tag{2.4}$$

$$\overline{R_{ii}} = A \text{ x } A^H. \tag{2.5}$$

The total undesired signal correlation matrix is calculated as

$$\overline{R_{uu}} = \overline{R_{ii}} + \overline{R_{nn}}\ , \tag{2.6}$$

$$\overline{R_{xx}} = E[\overline{x}\ \overline{x}^H] = \overline{R_{ss}} + \overline{R_{uu}}\ , \tag{2.7}$$

where $\overline{R_{xx}}$ is the total signal correlation matrix and $\overline{R_{nn}}$ is the noise correlation matrix.

The optimum weights are calculated using the Wiener Hopf solution, by solving the gradient of the expected value of MSE equated to 0, to obtain the condition for maximum MSE [14]. This leads to the product of the two correlation matrices:

$$w\overline{_{MSE}} = \overline{R_{xx}}^{-1} \text{ x } \overline{r}\ . \tag{2.8}$$

Thus, with the knowledge of the direction of the PU receivers and the intended MC receiver, the optimal beam may be formed.

2.3.6 Simulation Results - Smart Antenna Implementation

The minimum MSE technique that was described in [14] has been chosen as the implementation of smart antennas in our work. The parameters used for the implementation are chosen to be N = 10 elements in the antenna array and d = quarter wavelength at 700 MHz of inter-elemental spacing.

The following figures show an illustration of this technique by plotting the beam patterns for different instances. These are very relevant to the manner in which the smart antennas are implemented in this thesis.

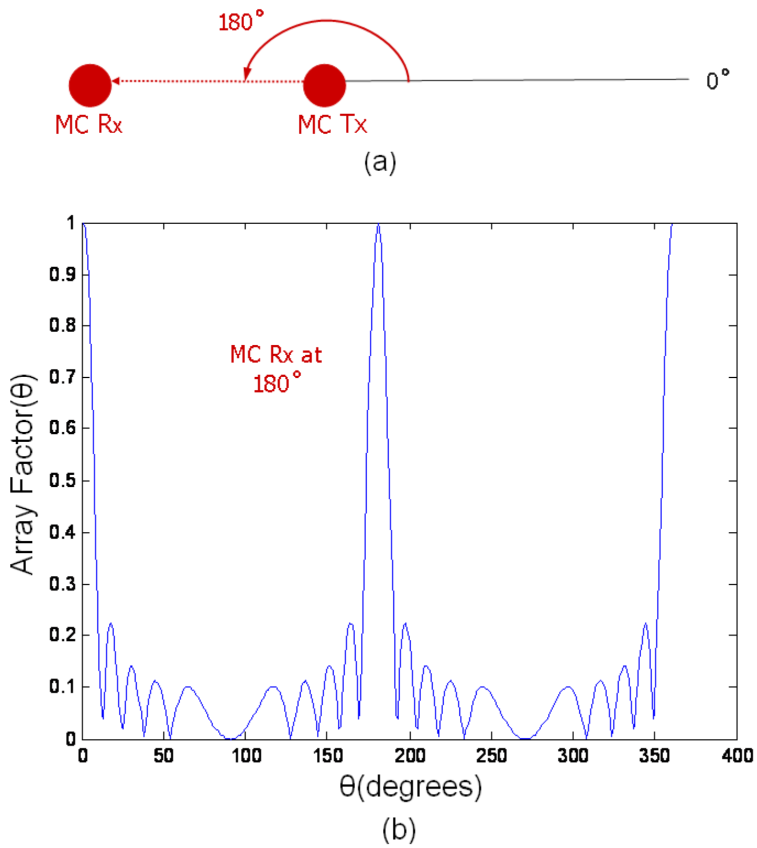


Figure 2.8 - Smart Antenna Illustration: No PU Receivers

The Array Factor of an antenna array defines its radiation pattern. Figure 2.8(b) shows the plot of the Array Factor generated using the MMSE technique for a transmitter communicating to its receiver positioned at 180˚ from its position, as shown in Figure 2.8(a). In this case, the algorithm does not have to deal with steering side lobes to accommodate the presence of any interferers. It is seen that there are two main lobes in the plot and multiple side lobes. The maximum number of nulls in the array factor is always one less than the total number of elements, N. Hence, this limits the number of PU receivers that can be accounted for through null positioning of a single transmitter to (N-1). It shall be seen in succeeding chapters that our implementation employs a positioning system. Using the knowledge of the positions of PUs, prioritization can be established to account for the PU receivers in the closest vicinity of an MC transmitter, if there are more than (N-1) PUs in the system.

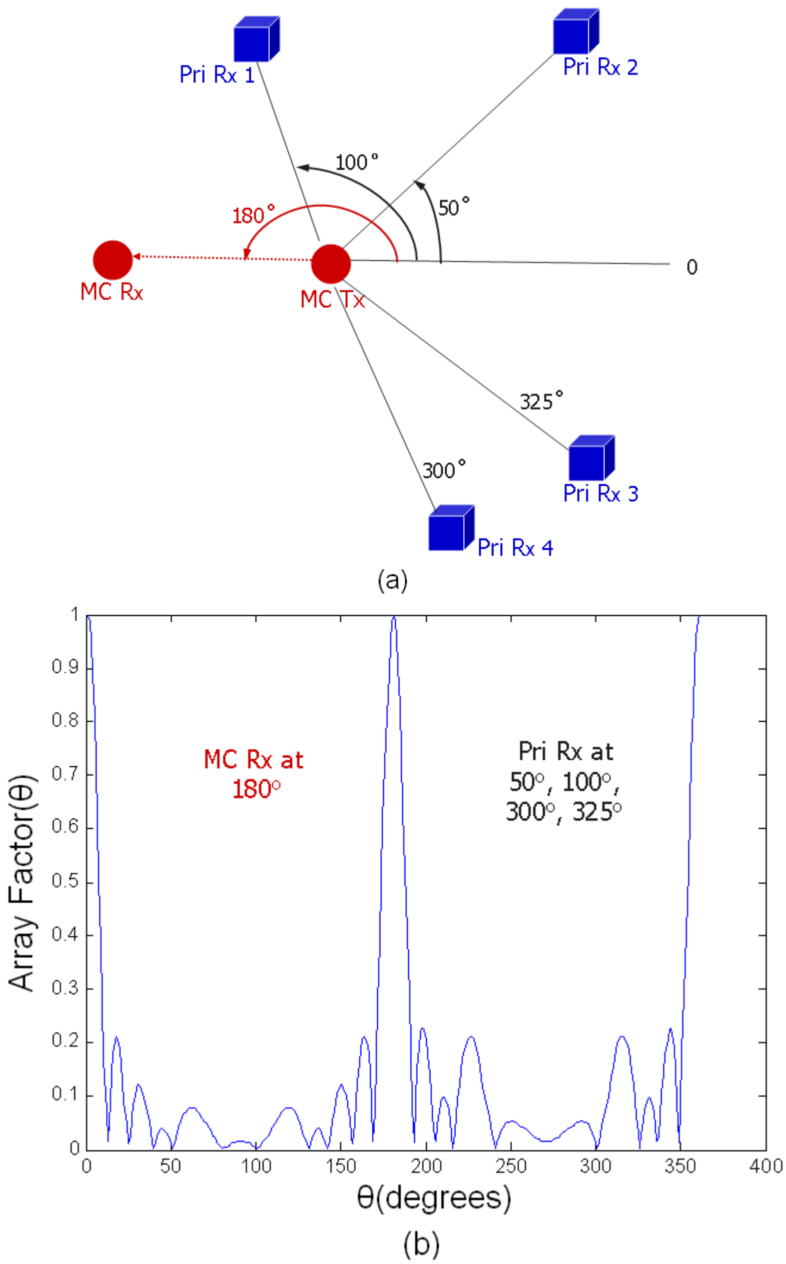


Figure 2.9 - Smart Antenna Illustration: Four PU Receivers

Figure 2.9 (a) shows a scenario where the MC receiver is at the same 180˚ angle from the MC transmitter. However, there are four PU receivers in the vicinity of the MC transmitter, aligned at angles 50˚, 100˚, 300˚ and 325˚ with respect to the MC transmitter. The goal is now to modify the transmission such that nulls are placed in the angles at which the PU receivers are aligned, without modifying the main lobe. Using the MMSE technique, the optimal inputs to the array elements, which would satisfy these requirements, are calculated. Using these, the array factor is calculated and plotted in Figure 2.9 (b). It is seen that nulls are now present at the angles at which the PU receivers are aligned, to satisfy all requirements. The default array factor that was plotted in Figure 2.8 without null positioning requirements has significantly been modified to account for the PU receivers. Thus, the near zero transmissions at the PU receiver angles using the MMSE technique greatly reduce the interference caused to the PU receivers.

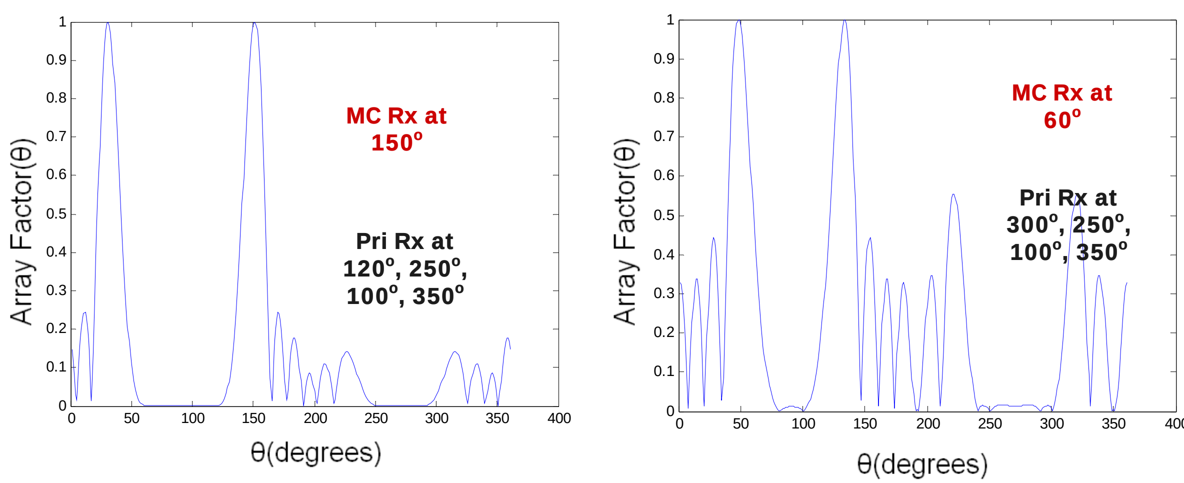


Figure 2.10 - Smart Antenna Illustrations: Other Scenarios

Figure 2.10 shows the array factors of the MC transmitter generated for two other scenarios, for different positions of the MC receiver and of the PU receivers. The MMSE technique proves to be efficient in positioning of nulls to reduce interference imposed on PUs by MC transmissions, and is chosen in our implementation.

2.4 Summary

In this chapter, we have discussed the two major technologies in this work, namely Cognitive Radios and Smart Antennas. Their salient features that find themselves applicable to the system at hand have been elaborated. In chapter 3, it shall be seen how these technologies are intelligently combined in our proposed model, to achieve spectral efficiency in a WMN, while effectively reducing interference caused to the PUs due to its operation.

Chapter 3

3. Cognitive Wireless Mesh Networks (CWMNs) with Smart Antennas

3.1 Introduction

Recently, the wireless communication industry has been growing at a very rapid pace while data transfer requirements have been increasing at an exponential rate. Severe under-utilization of licensed frequency bands is prominent among many television broadcasting stations, which prompted the Federal Communications Commission (FCC) to consider significantly better bandwidth utilization by deploying Cognitive Radios (CRs) for unlicensed wireless devices that could co-exist with the licensed Primary Users (PUs). Additionally, the FCC imposed a spectral mask on the transmission power of these unlicensed Secondary Users (SUs) so as to mitigate the interference on the PUs.

As previously described, a typical Wireless Mesh Network (WMN) consists of multiple Mesh Routers (MRs), each of which provides service to Mesh Clients (MCs). In its default state, a WMN operates in the standard ISM band (2.4 GHz). A CWMN, on the other hand, as the name implies, deals with incorporating CR capabilities to the WMN. This essentially means that the

CWMN is capable of co-existing with PUs, by utilizing portions of licensed spectrum that are unused for certain time durations. Such portions of unused spectrum appear seemingly sporadically and are referred to as white spaces. We explore to use these white spaces most efficiently for the CWMN by having MRs that experience bad channel conditions in their default band of operation shifting the operating frequency to the licensed spectrum. Efficient spectral utilization would encourage load sharing among numerous MRs in a WMN and hence, could increase the throughput. MRs that decide to change their operating frequency, change communication channels between MR-MC and MC-MC to the licensed band; however MR-MR and MR-Gateway communication still remains in the default channels.

3.2 Need to go beyond Omni-directional transmissions:

Each MC in a typical WMN usually employs omni-directional antennas, due to associated cost and ease of design. This may be adequate in a typical CR environment which would involve just one pair of SU nodes shifting operation into the primary band. Since there would be essentially only one secondary transmitter and receiver pair involved, omni-directional transmissions may be sufficient to maintain interference caused to the PUs within required limits. However, our system model calls for an entire cluster of MCs shifting its operation to the primary band. In such a system where multiple SU transmitters need to change, it would not be adequate to have omni-directional antennas at each node as it would cause a lot more interference to the PUs. Hence, a more efficient form of transmission is desirable. Here, we propose a scheme that reduces the interference to PUs by cognitive positioning of nulls through the side lobes of the antennae included in the SUs.

3.3 Two Tier Approach to Spectral Efficiency

The approach proposed here is essentially directed toward improvement of spectral efficiency to a large enough extent necessary for a successful operation of a CWMN. Hence, it uses a two tier approach to maximize spectral efficiency as shown in Figure 3.1:

- **Load Balancing using CR** – Load is said to be balanced within the CWMN between its default spectrum of operation and the licensed spectrum. The cluster(s) of MCs that shift operation benefit from the unoccupied PU's channel, and experience good channel conditions as opposed to the default band of operation from which operation is shifted due to bad channel conditions. The clusters that still maintain operation in default bands also benefit because such shifting causes the remaining default bands to have lesser traffic.

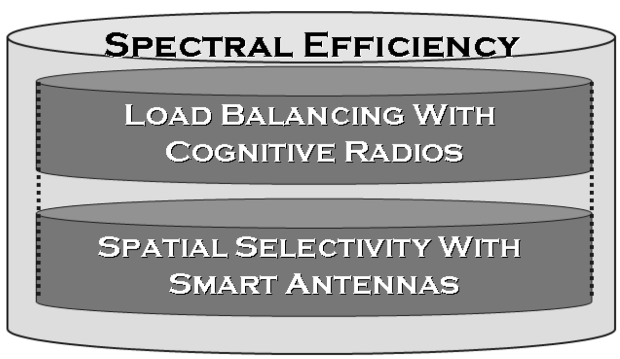


Figure 3.1 - Two Tier Approach to Spectral Efficiency

- **Spatial Selectivity with Smart Antennas** – As previously described, omni-directional antennas would simply prove to be too inefficient when implemented in a CWMN due to much more stringent interference requirements. Hence, we propose an efficient form of directional transmission through smart antennas (SAs). The MCs equipped with SAs concentrate their transmission energy towards the intended receivers, thus causing other

MCs to receive smaller interference and enabling their otherwise forbidden operation (Carrier Sense Multiple Access – Collision Detect, CSMA-CD protocols in 802.11). MCs will also be capable of directing their side-lobes of transmission away from the primary receivers, so as to minimize the interference caused to the licensed PUs.

3.4 System Model

The system under consideration is as depicted in the Figure 3.2. It consists of a set of PUs and a set of SUs. The PUs have a set of channels licensed to them, numbered 1 to M. Hence, they may choose to operate on these channels. The SUs operate in the vicinity of the primary communicating pair.

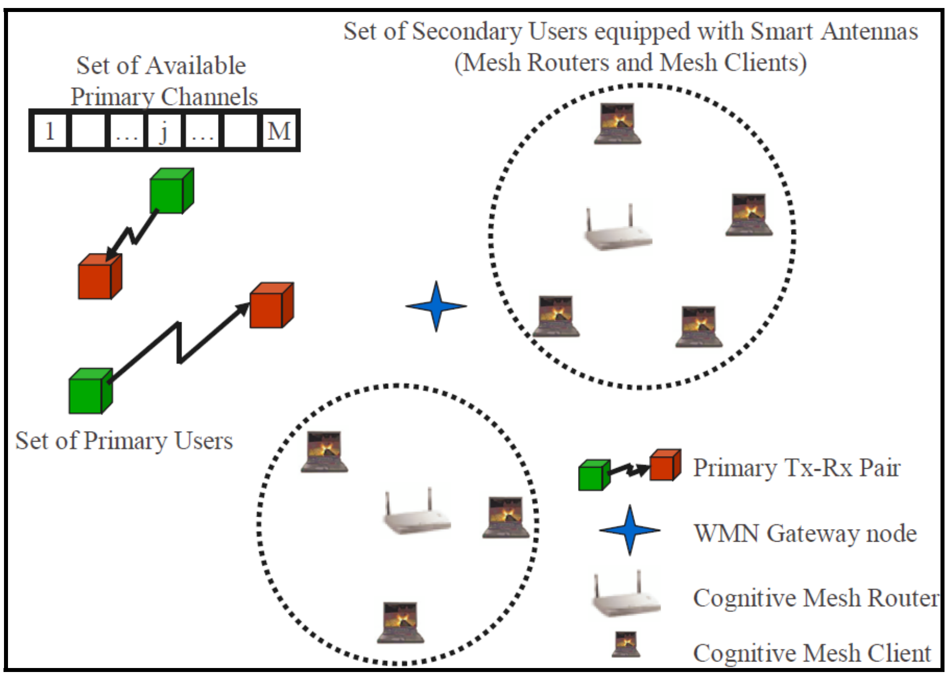


Figure 3.2 - Schematic Diagram of the System Model

There also exists a set of SUs, which comprises of cognitive MRs and cognitive MCs in the CWMN. As shown in Figure 3.2, the SUs are equipped with Smart Antennas that could achieve the required transmission efficiency. There is a central gateway node that simply performs the default functions as in any typical WMN, i.e. it does not participate in any unlicensed dynamic spectrum access. The cognitive cluster that decides to shift operation to the licensed band does so by occupying M available channels licensed to PUs. The following section describes how a certain cluster (referring to a MR and its MCs) decides to shift its operation to the licensed band and how it decides which of the M channels to shift to.

3.5 Operation of Load Balancing Algorithm

3.5.1 Decision of MRs to shift operation

The first step by the CWMN is to decide which MRs need to shift their operation to the PU's band. This ought to be a distributed decision, taken individually by each MR, based on its own channel conditions. If any MR is experiencing poor conditions in its current state of operation, it would not be capable of providing good service to its MCs and may decide to shift its frequency band of operation to the PU's licensed band.

The signal-to-noise-interference ratio (SINR) that the MR faces is used as the criterion to define if an MR should shift. As shown in Figure 3.3, in Step 1, each MR individually calculates the SINR that it is experiencing during communication with its MCs. In this case, if the observed SINR is less than 3 dB for a considerable duration, then that MR may decide to shift the communication frequency band it uses to exchange information with the MCs and among MCs to the PU's band.

Once an MR has decided to move to the PU's band, the next phase is to select which primary channel to move to. The channel must be selected so that interference caused to the primary system may be kept to a minimum. This means that the knowledge of the channel occupancy in the vicinity of the cluster is needed to make this decision. Hence, this phase is divided into two steps, namely spectrum sensing and channel allocation.

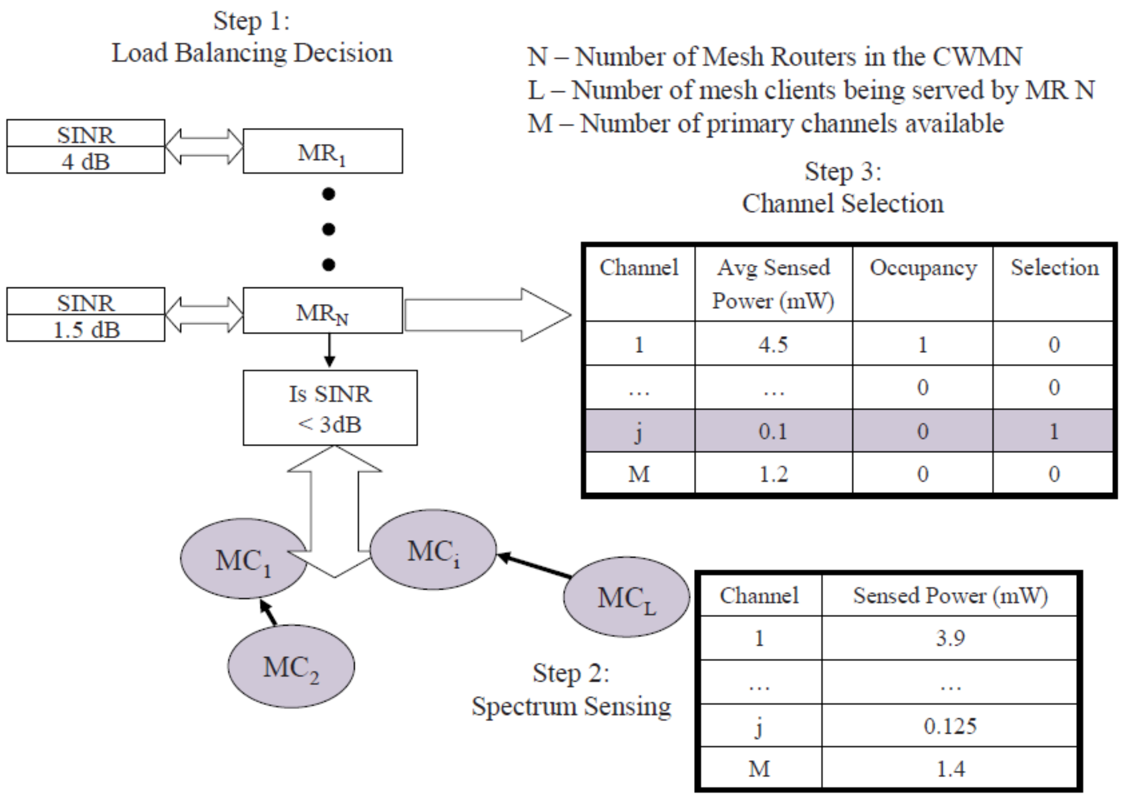


Figure 3.3 - Schematic Diagram for Load Balancing performed in the CWMN

3.5.2 Spectrum Sensing

As shown in Figure 3.3, Step 2 is labeled as spectrum sensing. Since the cognitive cluster will shift entire operation into the PU's band, the channel conditions within the entire boundary of the operation needs to be analyzed. This is because a PU's transmission close to one MC would be picked up by that MC, but could possibly go undetected by another MC served by the same MR. Hence, Step 2 involves each MC tuning its antenna to every available primary channel and making power measurements. It transmits this information to the MR which makes its channel selection decision based on this information.

3.5.3 Channel Selection Decision

Step 3 in Figure 3.3 is the channel selection decision performed by the MR with information about the power measurements collected from its MCs. To obtain an overall picture of the conditions, it computes an average over the sensed powers from all the MCs. As shown in Figure 3.3, these average values are tabulated and analyzed. In this example, it is seen that the highest average power for all PU's channels has been sensed on channel 1. The MR thus estimates that the closet PUs in its vicinity are communicating over channel 1. It is also important to note that the channel M has a higher sensed power, even though it is the farthest frequency from the PU's channel occupancy estimation. This could represent the possibility of another PU being located in a close proximity of the SU cluster. This illustrates that in many cases, when multiple PUs are involved, the best channel for communication may not be the channel farthest in frequency from the primary channel occupancy estimates. If the lowest average power is sensed on channel j, it indicates that the operation of the cluster in channel j would cause least interference to the PUs.

3.6 Interference Reduction by Directional Transmissions

After channel selection, the next step is to begin operation in the selected channel. In the load balancing decision algorithm, the MR shifts its operation to the primary channel selected and uses orthogonal frequency division multiple access (OFDMA) communication between the MCs and the MR and between the various MCs, as it is suitable to CR operation [15] [16].

3.6.1 Omni-directional Transmissions

Figure 3.4(a) shows the MCs communicating with each other and to the MR using omni-directional antennas. Since in this case, an entire cluster moves its operation into the PU's channel, the transmission powers from each MC contributes entirely to the interference at the primary receivers. As a result, the SINR observed at the PU receivers are quite low. Interference is also reduced to some extent by selecting the best channel. Hence, the inherent disadvantage of this scheme is the omni-directional transmission.

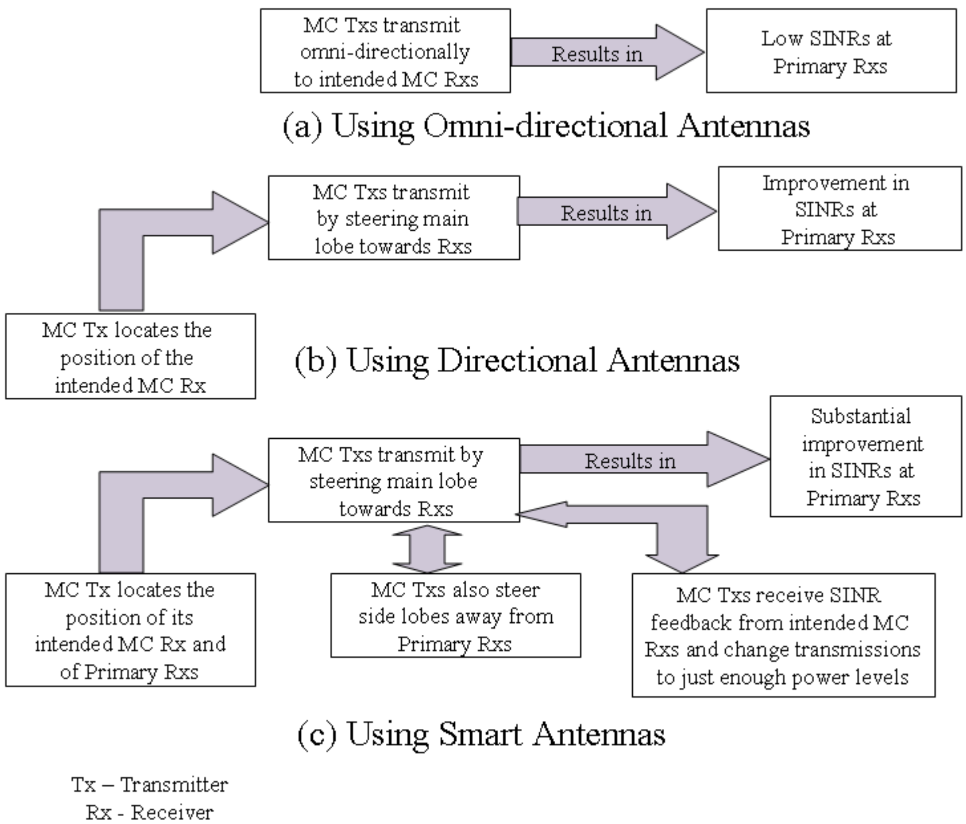


Figure 3.4 - Schematic Diagram for Interference Reduction performed in a CWMN using Directional and Smart Antennas

3.6.2 Directional Transmissions

Figure 3.4(b) shows the MCs communicating with each other and with the MR using directional antennas, which is a logical next step in limiting the omni-directional transmission. It involves the MCs concentrating their transmissions in the direction of the intended receiver. For this, the MCs require knowledge of the positions of the intended receivers. A global positioning system or a UWB positioning system as described in [17] can be used for this purpose. With this knowledge, an MC is capable of steering its main lobe transmission towards the intended receiver. The disadvantage of such an approach is that no directional transmission is perfect, i.e., it has a certain small amount of power in other directions, also called the side lobes. Hence, these side lobes would cause interference to the PU receivers, even though far lower than that in the omni-directional case. Using directional antennas provides a notable improvement in the SINR at the PU receivers.

3.6.3 Smart Antenna Transmissions

Though it is not possible to completely eliminate side lobes using smart antennas, it is possible to control their position and steer them as per requirements. The use of smart antennas for MCs communication is shown in Figure 3.4(c). The smart antennas are used to not only direct transmissions towards intended receivers, but also steer side lobes away from the PU receivers, so that the interference caused to them is further reduced. Hence, as in the directional antenna case, the MCs would utilize a positioning system to obtain the location of the intended receiver and the PU receivers. Transmissions are conducted with this knowledge.

3.7 Decision Processes of the MR during Operation

Figure 3.5 shows the flow diagram of the decisions made at the MRs. The choice of whether an MR should shift the frequency band of operation is a distributed one, taken individually by each MR and is based on the channel conditions being experienced. In this case, if the SINR at an MR is poor, specifically less than 3 dB, it decides to shift operation into the PU's band due to current inability to provide satisfactory service to its MCs.

Once an MR has made this decision, it engages its associated MCs in spectrum sensing. The MR obtains power measurements made by each of the MC it serves and tabulates the average sensed powers (ASPs) for all the available primary channels over all the MCs. It then iterates through the ASPs to determine the channel with greatest sensed power. It makes this channel as the estimated channel of PU's operation. It also finds the channel which has the minimum sensed power and selects this channel as the most suitable as the channel to switch operation into.

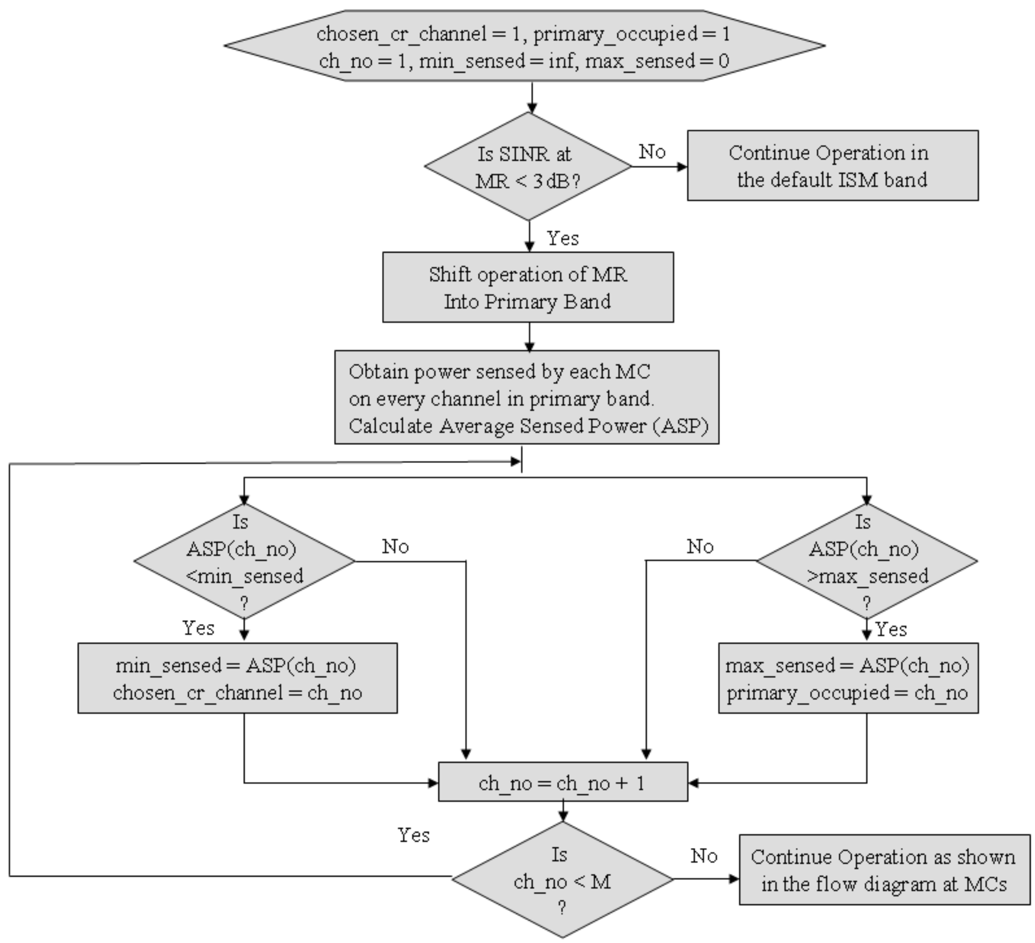


Figure 3.5 - Flow Diagram of the Decisions taken at the MR

3.8 Implementation

3.8.1 Load Balancing Algorithm

Algorithm 3.1 describes the Load Balancing stage of our mechanism. It involves deciding which MRs need to shift their operation to the PU's band and selection of the right channel to shift to by employing Spectrum Sensing. As shown by lines 3 to 8, the SINRs at each MR is calculated and if the SINR observed in the current band is low, specifically less than 3 dB, then the MR would be incapable of providing good service to its MCs and hence shifting operation would be a good option. It is then flagged for the change. The MRs now have to decide what channel to switch to.

```
//Load Balancing Algorithm
    1:  Input: Set of Mesh Routers in the CWMN, MR_set; Number of MCs in each
        MR, no_of_MCs; Set of available primary channels, chan_freq_set
    2:  Output: MRs that need to shift operation to primary band, Estimate of the
        primary channel occupancy, pri_occupancy_estimate; Primary channel chosen
        for shifting operation to, chosen_cr_channel
    3:  for MR = 1 to length(MR_set) do
    4:      Calculate SINR(MR) by analyzing the average SINR from its MC
            communications
    5:      if SINR(MR) < 3dB then
    6:          shifting(MR) = 1
    7:      end if
    8:  end for
        //Spectrum Sensing Section
    9:    for MR = 1 to length(MR_set) do
    10:     if shifting(MR) = 1 then
    11:         for MC = 1 to no_of_MCs(MR) do
    12:             for channel_no = 1 to length(chan_freq_set) do
    13:                 Compute Sensed_power(MR, MC, channel_no)
    14:             end for
    15:         end for
    16:     end if
    17:   end for
    18:   Sensed power information from all MCs are sent to the MR
          //Channel Selection Section
    19:   for MR = 1 to length(MR_set) do
    20:     if shifting(MR) = 1 then
    21:         avg_sensed_power = mean(Sensed_power(MR,:,:))
    22:         pri_occupancy_estimate(MR) = index_of(max(avg_sensed_power))
    23:         chosen_cr_channel(MR) =  index_of(min(avg_sensed_power))
    24:     end if
    25:   end for
```

Algorithm 3.1 - Load Balancing

Spectrum Sensing is pivotal is the next pivotal stage in making this decision. This is described in line 9 where every MC served by the MR makes a measurement of the power it senses on every PU channel available so that an overall estamation about the channel conditions in the whole network is made. Then, each MC sends its power measurements to the MR which makes the decision of which channel to switch to.

The next step is to find the channel in which the MR can shift operation into, that would cause least interference to the PU. Thus, channel selection is carried out by an analysis of the sensed powers. This is done in lines 19 to 25 if the MR is scheduled to shift operation and has performed the necessary spectrum sensing. Line 21 averages the sensed powers received over all the MCs and provides an estimate of the channel occupancy in the vicinity of the MR. Line 22 estimates what the channel that a PU in the vicinity of the cluster is using as the channel in which maximum power is sensed. Line 23 decides the best channel to switch operations to as the channel in which minimum power is sensed.

3.9 Simulation Setup

Figure 3.6 depicts the simulation scenario used in this chapter. The WMN is made up of a gateway node and four MRs in an area of 300m x 300m. Each MR serves 10 MCs. The MCs operating under an MR are placed randomly in a 100m x 100m area. A scenario is chosen such that a PU transmitter and receiver pair (also placed randomly within the 100m x 100m area) operates in the vicinity of each cluster around MR. The four primary transmitters use a transmission power, each chosen randomly between 0.5 and 1.5 W.

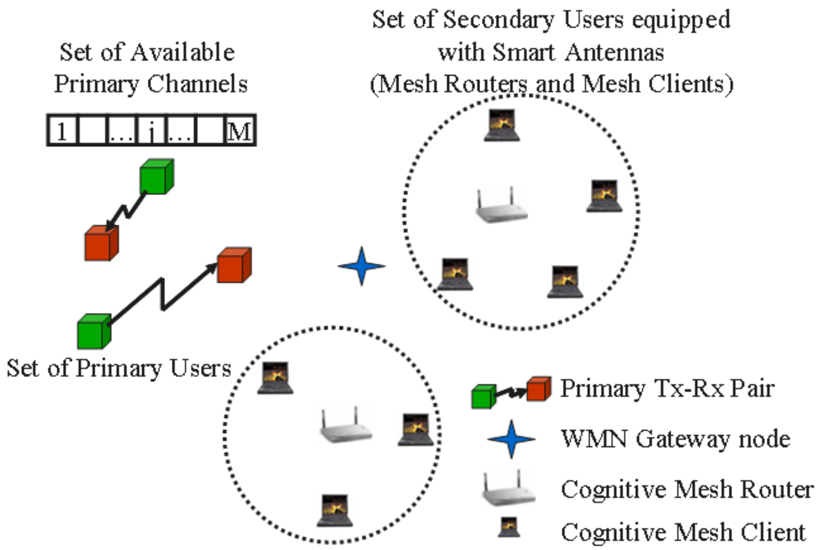


Figure 3.6 - Simulation Setup

The MCs operate using Orthogonal Frequency Division Multiple Access (OFDMA). This is relatively a bad case scenario in terms of reduction in interference to the PUs, as OFDMA allows multiple users to transmit at the same time on a single channel. 20% of the MC packets are assumed to be of high priority and MCs transmit at a higher power level than other MCs so as to direct transmissions directly to the MR, thereby avoiding multiple hops that cause intolerable delays.

3.10 Performance Evaluation

3.10.1 Spectrum Sensing

Simulations have been performed using the model described in Section 3.4. To illustrate spectrum sensing using this simulation scenario, we first consider 7 available licensed channels between 700 MHz and 735 MHz. Each PU transmitter randomly selects a channel from the available pool for its operation. The transmission power of each is chosen randomly between 0.5W and 1.5W. This initial scenario considers one PU pair in the vicinity of the mesh clusters as described in the system model. Spectrum sensing processes are also analyzed in scenarios considering 32 available licensed PU channels, with multiple PU communication pairs in the vicinity of the mesh clusters.

Spectrum sensing is a critical mechanism in the operation of the CWMN. This process enables the MR to sense which parts of the spectrum are occupied and which parts are open for access. Hence, a higher degree of accuracy is desirable in this component. The 802.22 standard governing this form of unlicensed dynamic spectrum access defines the maximum probability of error in the channel occupancy detection to be 10%. The aim of the simulation results depicted in Figure 3.7 is to show how Spectrum Sensing is performed and how accurate the process is for the system under consideration. Each segment in the figure represents MR power estimates gathered by averaging power measurements from each of the MCs it serves. The goal of the process is to estimate the channel occupancy by the PU's communication geographically closest to the mesh cluster. The channel that the closest primary transmitter uses and the channel of PU's occupancy estimated by the MR are listed above each segment. It is observed that the accuracy of this estimation can satisfy the requirements, but does suffer from errors due to reasons described here.

Figure 3.7 (a) and (b) demonstrate a simulation scenario in which each MC tunes its antenna to each of the 7 channels in the PU's band under consideration and makes a power measurement. Each MC reports 7 measurements to its serving MR. The MR averages these measurements over its 10 clients and obtains a graph. The sensed value in each channel is the result of primary channel usage from all four transmitters, including overflow from adjacent channels (Adjacent Channel Interference - ACI) as well as additive white Gaussian noise (AWGN). Adjacent channel interference calculations are based on [8].

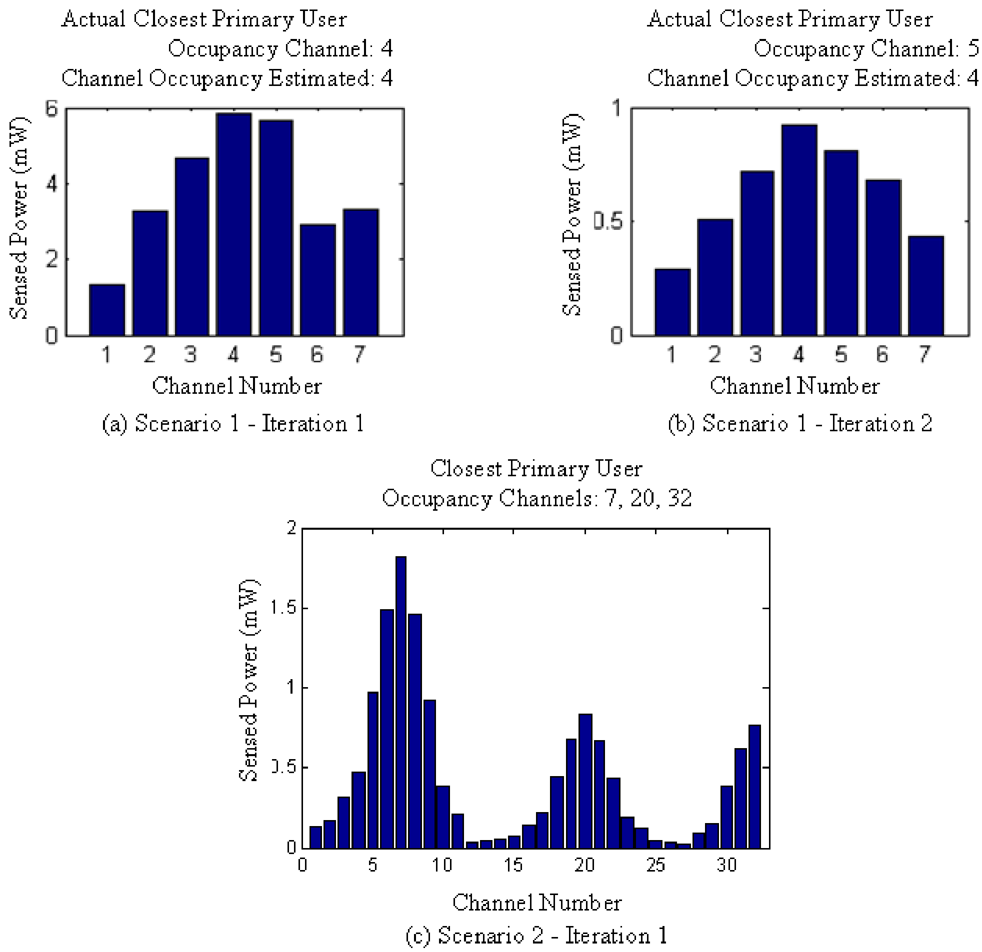


Figure 3.7 - Illustration of Spectrum Sensing in scenarios comprising:
(a), (b) - 7 available primary channels with 1 primary user in the vicinity of each MR
(c) - 32 available primary channels with 3 primary users in the vicinity of each MR

Figure 3.7(a) shows iteration 1 of the averaged value calculated by the MR that has decided to shift operation into the PU's band. The PU transmitter close to it occupied channel 4. As seen in the graph, the average sensed power is the greatest corresponding to channel 4. Hence, an estimate of the channels that are occupied by the primary system in the vicinity of the MR can be made.

Figure 3.7(b) shows iteration 2 of the averaged values calculated by the MR. The PU transmitter close to it occupies channel 5. However, the greatest sensed power is corresponding to the channel 4, due to a large ACI and AWGN at that point combined with the possibility that the primary transmitter 4 uses a smaller transmission power than the rest of the PUs. It is seen that due to these factors, the probability of correct channel estimation is ~ 98% when no noise was considered in the system. This was measured by analyzing the accuracy in estimation for 10,000 iterations. With the inclusion of Additive White Gaussian Noise into consideration, this probability fell to ~90%. By the 802.22 standard governing the mechanisms for dynamic access of unlicensed spectrum by CRNs, is considered to be satisfactory for an effective operation.

In such cases where multiple PU communication pairs operate in the vicinity of the mesh cluster, complexity in channel estimation is increased. Figure 3.7(c) shows an iteration of spectrum sensing results when 32 licensed channels from 700 MHz to 860 MHz are available, with three PU pairs in the vicinity of each CWMN cluster. It is seen that after averaging powers over all MCs, there are peaks in the plot corresponding to the channels being occupied by the nearby PUs. It is to be noted that each of the MCs served by the MR must take power measurements on each of the 32 available PU channels. It is observed that the process of spectrum sensing becomes much more tedious and complex as the number of available PU channels increases, but it is still possible to obtain them accurately.

3.10.2 SINR Improvement

The ultimate goal of our work is to enable operation of the CWMN while limiting the interference caused to the PU network due to this operation within permissible limits. Hence, our primary motivation must be that the primary communication continues without hitches. To ensure this, it must be guaranteed that the SINRs at the PU receivers stay within the operating conditions. The following simulation results pertain to a scenario where the location of the MCs and the primary communication pairs is determined randomly. The SINRs at each of the four primary receivers is observed at a given instant where all communication links under consideration are active.

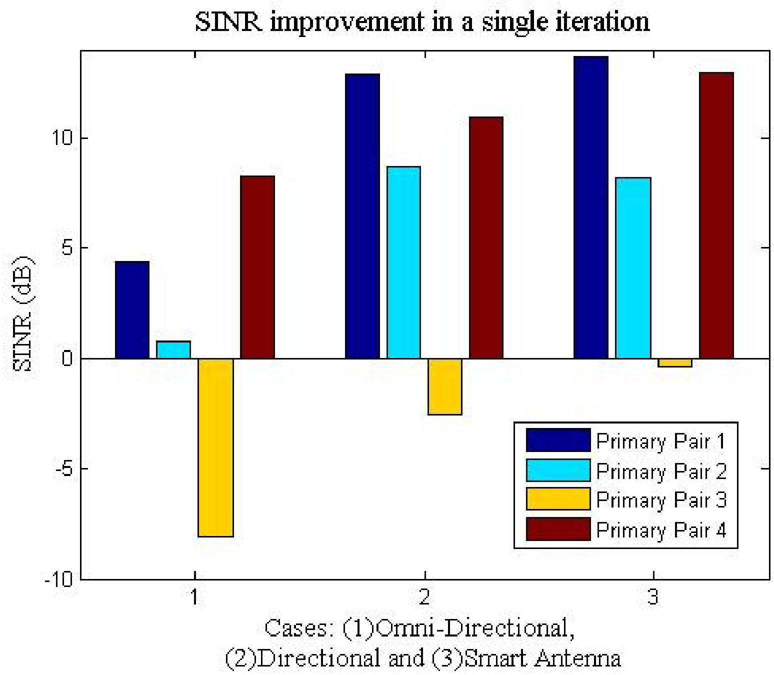


Figure 3.8 - SINR Improvement

In Figure 3.8, the SINRs observed at the PU receivers are plotted and the improvement is seen as the directional and smart antennas are used at MCs' transmitters. The first set of four bars depicts the SINRs at the four primary receivers when omni-directional antennas are used. Sets 2 and 3 correspond to the same setup, except that the omni-directional antennas are replaced by directional and smart antennas. Set 4 represents the case of using smart antennas implementing the SINR feedback mechanism at the MCs.

In this particular iteration, the four primary transmitters use powers approximately at 1.5W, 0.9W, 0.8W and 0.7W respectively. The MR in the segment closest to primary pair 2 moves operation into the PU's band. The result of random positioning in this case is a comparable distance between the primary transmitter and receiver pairs 1, 2 and 4; however pair 3 has been more widely separated. As a result, pair 3 suffers from poor SINR. The primary receiver 2 is positioned very close to the MC transmitters and hence suffered poor SINR in the omni-directional antenna case, even though the signal power is kept high.

A minimum SINR requirement of 3 dB is considered as the criterion for any feasible communication. It is observed that only two of the four pairs satisfy this requirement in the omni-directional antenna case. When directional antennas are implemented, three of the four pairs satisfy the 3dB requirement, however one still experiences an SINR less than 3dB as a result of the side lobes from the transmissions of the MCs. When smart antennas are incorporated which are capable of directing their side lobes away from the primary receivers, all devices shown an improvement, but still one suffered poor SINR. As will be shown in the next chapter, after the SINR feedback mechanism has been implemented at the MCs, all the four primary pairs have an acceptable SINR performance.

3.10.3 SINR PDF

Due to highly arbitrary positioning of the MCs and PUs and random selection of transmission powers at the primary communication pairs, a single iteration would obviously not be sufficient to judge the system performance. A statistically accurate representation calls for the experiment to be repeated multiple times and the number of primary pairs experiencing satisfactory communication requirements is needed to be studied. To do this, the simulation is performed over 10,000 iterations and on each iteration, the setup considered regarding the variable parameters is the same for all three cases of the antennas used. The density functions resulting of this approximates to a Gaussian representation; itself an indication of the validity of the sample size.

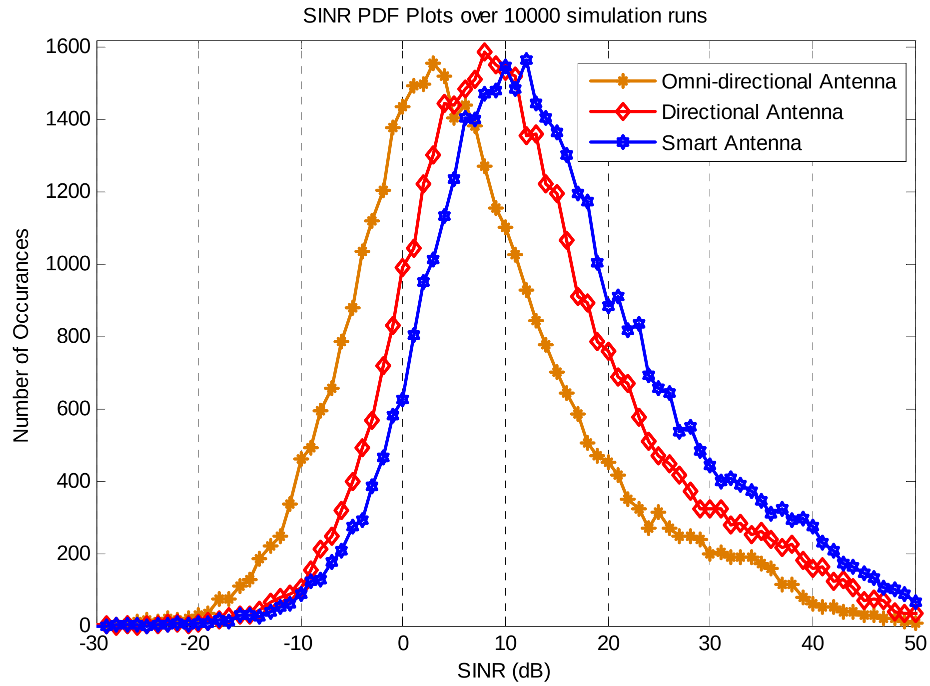


Figure 3.9 - Plot of SINR PDFs

Repeating this simulation over 10,000 random iterations, density function is plotted as shown in Figure 3.9. Each iteration considers four primary receivers. The SINR pdf is hence plotted as shown, over the SINRs experienced by the 40,000 primary receivers. It is seen that the SINR pdf observed in each case of different antenna implementations for the same scenarios is an almost Gaussian curve. In the case of each MC with its default case of having an omni-directional antenna, the curve is centered around 2.5dB. Only 26,185 of the 40,000 primary receivers satisfy the 3 dB requirement. Incorporation of directional antennas enables the MCs to direct their transmissions primarily in the direction of the intended receivers. This causes a 5.5 dB shift to the Gaussian SINR pdf curve to being centered around 8 dB allowing 33,249 pairs satisfy the 3 dB requirement. When smart antennas are implemented, the MCs are capable of not only directing their transmissions toward the intended receivers, but also direct transmissions away from the PU receivers, thus increasing the SINRs experienced by them. The Gaussian curve of SINR pdf in this case centers around 10 dB, experiencing a 7.5 dB gain over omni-directional antenna, enabling 35,541 pairs to satisfy the SINR requirement.

3.11 Summary

In this chapter, we have described the operation and setup of CWMNs and incorporated smart antennas in CWMNs for interference reduction to PUs. First, we developed a load balancing strategy to switch an MR with its constituent MCs to the open licensed spectrum based on its received signal strength. We have utilized a distributed spectrum sensing approach at the shifting MR to select the best channel to switch to. Finally, we have made an in-depth comparison of interference imposition on the PUs while using omni-directional, directional, and smart antenna. Our simulation results indicate a substantial improvement in the interference reduction using smart antennas over the others.

Chapter 4

4. Adaptive Transmission Powers in the CWMN

4.1 Introduction

As was explained Chapter 3, the ultimate goal of this work is to enable the operation of CWMN while still restricting the interference caused to the PUs due to this operation within permissible limits. Hence, the approach in Chapter 3 for limiting the interference by MCs to PUs follows spatial selectivity. Another approach introduced in this chapter intelligently combines spatial selectivity with transmission power control at the MCs (P_t) that effectively reduces the interference caused.

The protocol considered in Chapter 3 makes MCs operate at a fixed P_t, that provides acceptable performance. This is inefficient as some of the transmissions do not require such high power if the intended receiver is close by or if the interference is not too high. This is also harmful to the system as higher power transmissions cause more interference to the PUs. It is thus desirable to have the MCs transmitting at “just enough” power levels by adapting the transmission powers (P_t) at the MCs as per the scenario.

It is obvious that higher the transmission power of the MCs is, higher will be the interference to PUs (and vice versa). The extent could vary, depending on the distance between the frequencies of operation of both the MCs and PUs and the geographical separation between the two. Therefore, any reduction in P_t would benefit the PUs in terms of increasing their SINRs. It is, of course, illogical to reduce P_t to a level below which normal operation cannot take place. Thus, it must first be ensured that the MCs do operate at the power levels required for a normal operation. The primary goal of the experiments elucidated here is to achieve even better SINR performance of the PUs by making the MCs operate at "just enough" power levels for sustainable communication.

4.2 System Setup and Schemes

Simulation experiments have been performed using the same system model as that described in Chapter 3, with each MC incorporating smart antennas. The schemes considered here have been implemented on top of the running model of Chapter 3, that focused on incorporating smart antennas with the MCs. The major difference is the addition of adaptive P_t at the MCs. The variable P_t case is compared with the static P_t case, with both incorporating smart antennas at the MCs.

Two schemes are considered to include dynamic adaption of P_t :

(a) Empirical Formula Approach, and

(b) SINR Feedback Mechanism

4.3 Empirical Formula Approach

4.3.1 Basic Scheme

To overcome the inefficiency of a static P_t, an immediately obvious technique would be to vary the transmitted power depending on the distance of the intended receiver from the MC Tx. Since the position of the intended Rx is known, the distance can be calculated and the transmission power may be adjusted accordingly. It simply works on the principle that an intended receiver can be communicated by using smaller P_t if it is geographically closer to the transmitter and vice versa. An empirical formula is derived to compensate for the free space path loss which decreases with the square of distance. Free space path loss is inversely proportional to the square of distance and hence, the transmission power is varied as per equation (4.2):

$$MF = (1 - (\alpha/d^2)). \quad (4.1)$$

$$P_{t\_new} = P_t \times MF, \quad (4.2)$$

where MF is a multiplication factor used for the current transmission power and α is a constant greater than 1, defining the exponential increase of MF.

4.3.2 Limitations of Empirical Formula Approach

The major limitation of this approach is that only distance is taken into account and the experienced interference is neglected. It essentially tries to achieve equal SINRs at all MCs under the assumption that each MC Rx is subject to the same interference conditions, which is of course a highly questionable assumption. Thus, it cannot provide equal SINRs at all MCs.

Another by-product of the same fact is that the transmission power cannot be made greater than the default power, i.e., it is only aimed at reduction of P_t. As a result, though PU pairs benefit, some MC pairs already suffering high interference, may have their SINR drop below the

3 dB requirement. Thus, for a lower α, the minimum transmitted power of the MCs is reduced and hence the SINR benefit at the PU receivers is the maximized. However, this results in poor SINR performance at the MCs.

4.3.3 Simulation Results

The following simulation results depict the SINRs at the MCs. This parameter has not been analyzed so far, as our focus was primarily directed to the SINR performance of the PU system. The SINRs have been analyzed by a single iteration the system, with a random positioning of the constituent MCs and PUs, with each MC following spatial selectivity through smart antennas. MC SINRs over a set of 12 individual MCs are studied in section 4.3.4, each part of cluster(s) which had shifted operation to the primary band of operation.

4.3.4 MC SINR Performance before Change in P_t

Figure 4.1 represents the SINRs at 12 individual MCs, which operate using the default transmission parameters of equal P_ts as described in the system model of Chapter 3.

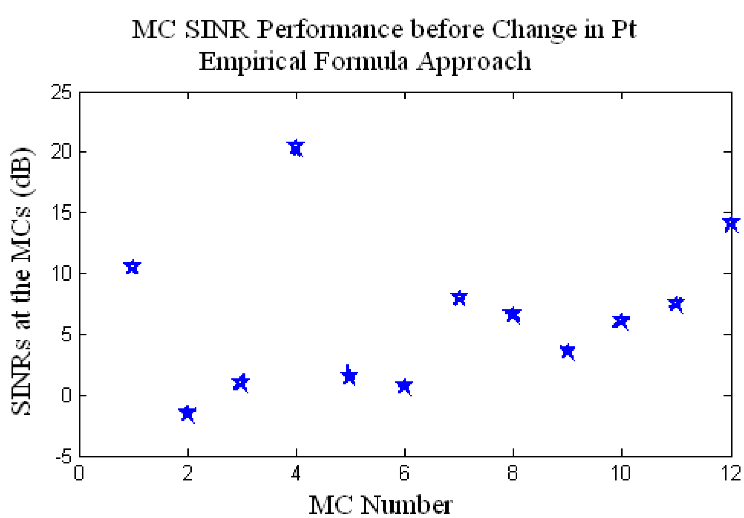


Figure 4.1 - SINR Performance at MCs before Change in Pt

The random positioning of the MCs implies random distances between MC Tx and Rx pairs. Thus, having equal P_t causes the MC SINRs to be distributed randomly. As seen, the SINRs in the iteration under study varied between -4 dB and 21 dB; an effective range of 25 dB.

4.3.5 MC SINR Performance after Change in P_t

Figure 4.2 gives the SINRs for the 12 MCs considered in the previous section, in the same positions, implementing the Empirical Formula Approach to varying P_t with the parameter α, as per equation (4.1), set to 90.

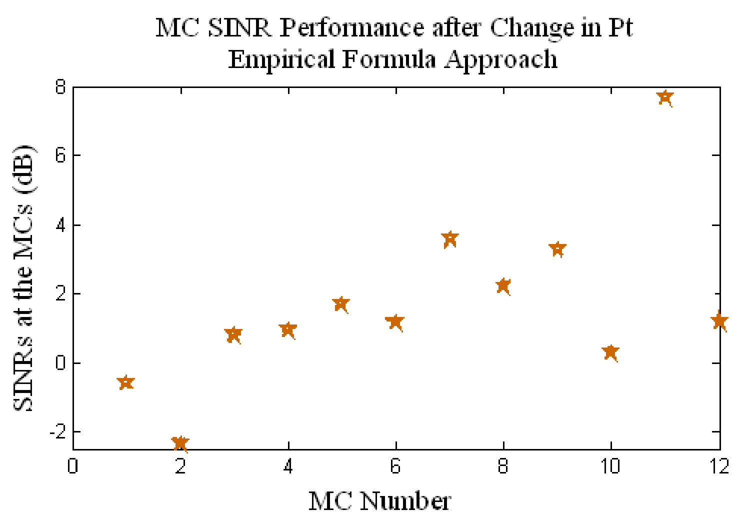


Figure 4.2 - SINR Performance at MCs after Change in Pt for α = 90

It is seen that after changing P_t at each MC, the SINRs of the MCs have been reduced to fall within limits of -2dB to 8dB, an effective range of 10 dB. The value of $\alpha = 90$ is a relatively aggressive situation at the MCs in terms of reduction of SINRs. This is a right step in the direction of reducing P_t to improve the SINR performance of the PUs. However, as detailed in section 4.3.2, the approach does not provide any benefit to the SINR performance of the MCs, but has a negative impact as seen in 4.3.6.

4.3.6 Long-run Performance

A single iteration is not enough to judge the performance of an approach in a system setup with multiple random variables. Hence, the method has been examined over 10,000 iterations, in a fashion similar to that described in the SINR PDF generation of section 3.10.3 and the improvements obtained are shown in Figure 4.3.

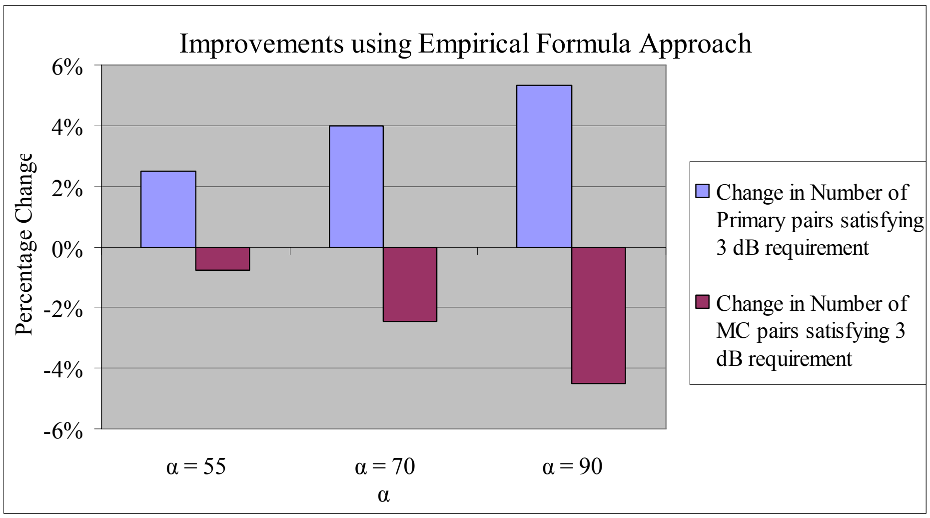


Figure 4.3 - Performance Evaluation: Empirical Formula Approach

Higher values of α represented a harsher restriction on the P_t at the MCs. This implies less interference to the PUs in improving their SINR performance. As shown in Figure 4.3, varying α from 55 to 90 causes substantial increase in the number of PU pairs satisfying the 3 dB requirement and doubles this factor from 2.5% to 5%. However, this improvement comes at a price of the SINR performance at the MCs, with the number of MCs losing required SINR performance degraded from 0.75% to 4.5%. Hence, a trade-off is present between the performances of the two systems.

4.4 SINR Feedback Mechanism

4.4.1 Approach

A more dynamic technique would be to vary Pt based on the SINR experienced at the MC Rxs. It involves having the receiver MCs piggyback the SINR that they experience to their transmitters with the acknowledgement packets. From this information, the transmitter can change its transmitting power to have the receiver follow a required SINR under current interference and distance conditions. By doing so, the transmitter may increase or decrease its power between limits to serve both the MCs by attaining required SINRs as well as the PU receivers as the MCs need not transmit at a more than required power level. Hence, this would be the ideal case of having the MCs transmitting at just enough power levels. Hence this is the approach that is chosen for the system in consideration. Setting a reasonable required SINR can account for changes in the interference and the channel conditions. If the SINR fed back is not within 0.3 on either side of the required SINR, the transmission power is updated as per the following simple relations:

$$SINR = S / (I + N), \tag{4.3}$$

$$= (P_t \times \beta) / (I + N). \tag{4.4}$$

$$SINR_{req} = S_{req} / (I + N), \tag{4.5}$$

$$= (P_{t\_req} \times \beta) / (I + N). \tag{4.6}$$

Dividing equation (4.6) by (4.4):

$$SINR_{req} / SINR = P_{t\_req} / P_t. \tag{4.7}$$

$$P_{t\_req} = P_t \times (SINR_{req} / SINR), \tag{4.8}$$

where S represents the signal strength received at an MC Rx and S_{req} the signal strength required to achieve a certain required $SINR_{req}$. I and N represent the Interference and Noise factors respectively. β is the path loss factor that decreases exponentially with the distance. P_{t_req} represents the transmission power that the MC should change to, so as to achieve $SINR_{req}$.

Equation (4.8) represents the manner in which the SINR Feedback mechanism varies the P_t from its earlier value based on the knowledge of the current SINR conditions at the MC Rx. What it boils down to is using a multiplication factor of $(SINR_{req} / SINR)$ on the earlier P_t.

4.4.2 Decision Processes of the MCs during Operation

Figure 4.4 shows the mechanism carried out at the MCs, implementing the SINR Feedback Mechanism for adaptive power control. As per default operating conditions, the MCs under their serving MR utilize OFDMA. Once the channel selection phase is complete, they communicate with each other and with the MR on the primary channel selected.

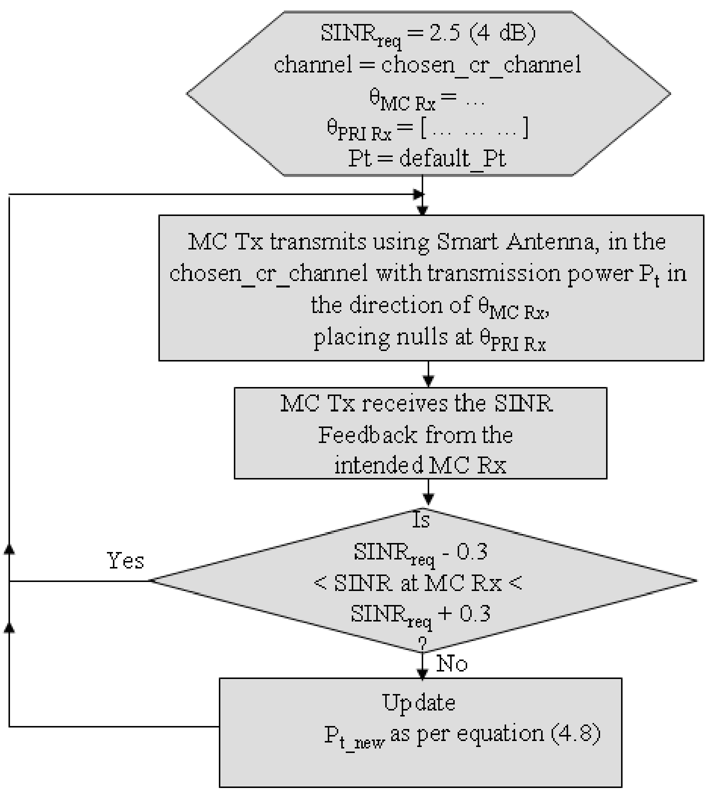


Figure 4.4 - Flow Diagram of the Decisions taken at each MC

As described in Chapter 3, each MC implements spatial selectivity in transmission. Using the locations knowledge of the intended MC receiver and of the primary receivers, the MC transmitters steer their main lobe and side lobes in the required manner. The MC Tx begins communication with the Rx using the default P_t. As communication continues, the MC Rx transmits the SINR it receives to the MC Tx. The Tx then checks if the SINR being experienced is within the limits from $SINR_{req}$. Ideally, these limits are 0, but they are set to 0.3 in this implementation to prevent having to change P_t for every SINR feedback received. If not, it re-calculates the P_t as dictated by equation (4.8) and resumes its operation.

4.4.3 Simulation Results

The following simulation results illustrate the SINRs at the MCs. Similar to section 4.3, the SINRs have been analyzed in a single iteration of a system, with random positioning of the constituent MCs and PUs with each MC implementing spatial selectivity through smart antennas. The SINRs over a set of 14 individual MCs are shown, being part of cluster(s) which had shifted operation to the PU band of operation.

4.4.4 MC SINR Performance before Change in P_t

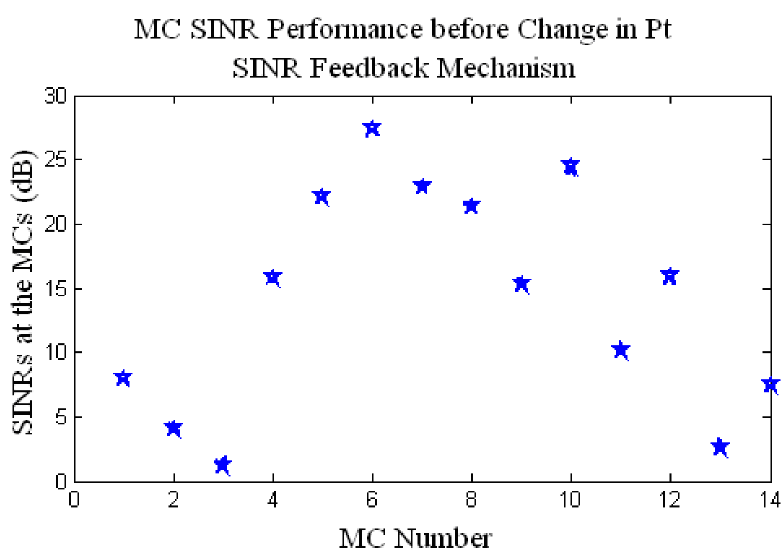


Figure 4.5 - SINR Performance at MCs before Change in Pt

Figure 4.5 represents the SINRs at 14 individual MCs, which operate using the default transmission parameters of equal P_ts as described earlier. The SINRs in the iteration under study varied between 1 dB and 28 dB; an effective range of 27 dB.

4.4.5 MC SINR Performance after Change in P_t

Figure 4.6 depicts the SINRs for 14 MCs implementing the SINR Feedback Mechanism of varying P_t, with the $SINR_{req}$ set to 4 dB.

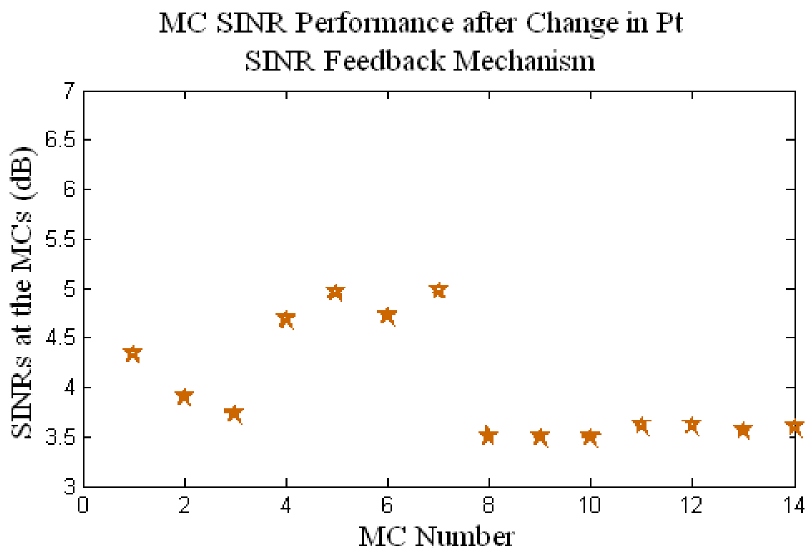


Figure 4.6 - SINR Performance at MCs after Change in Pt for $SINR_{req}$ = 4 dB

It is seen that after changing P_t at each MC as per the SINR Feedback Mechanism, the SINRs of the MCs are reduced to fall within limits of 3.5 dB to 5 dB, an effective range of 1.5 dB. The value of $SINR_{req}$ = 4dB is a relatively aggressive situation in terms of reduction of SINRs at the MCs. However, it is seen that all the MCs do satisfy the 3 dB requirements. It is also observed that the some MCs which were suffering poor SINRs have now had their performance raised to acceptable levels. It is thus a win-win situation for both the PUs and the SUs as the MCs truly achieve “just enough” P_t levels, as seen in Figure 4.6.

4.4.6 Long Run Performance

It is seen that as the $SINR_{req}$ grows, the MCs try to maintain a higher SINR for their own communication. As a result, they transmit at higher power levels. This causes interference to the PUs and results in decreased SINR at the PU receivers. It is observed that the least $SINR_{req}$ at the MCs is most beneficial to the PU system, providing greatest improvement in the number of PU pairs satisfying SINR requirements.

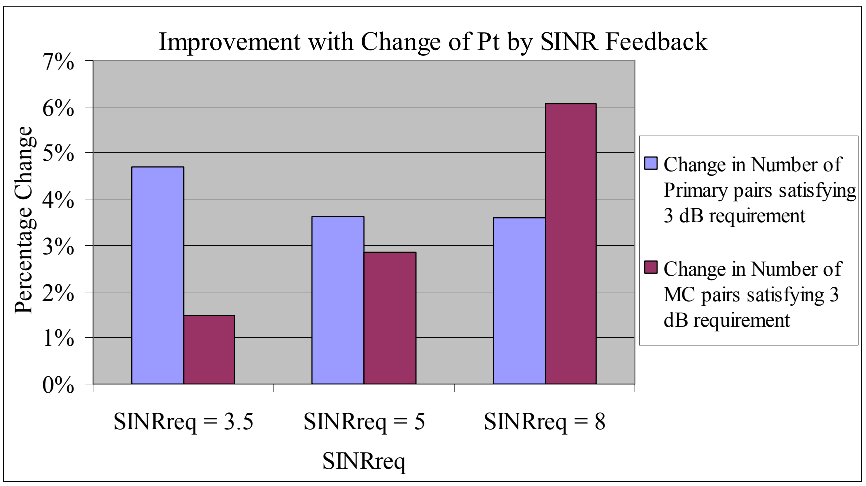


Figure 4.7 - Performance Evaluation: SINR Feedback Mechanism

Figure 4.7 shows the system performance improvement, incorporating smart antennas at the MCs when adaptive transmission power by SINR feedback is implemented. The limits used are:

Minimum Pt limit = 10% of the default Pt.

Maximum Pt limit = 5 x default Pt.

As shown, this mechanism seems to be a novel one, proving beneficial to both the MCs as well as to the PU receivers. This is because similar performance change is observed among all the MCs is enforced. MC pairs that show higher SINR performance are made to reduce transmission powers, thereby benefiting the PU receivers. MC pairs observing low SINR performance are made to increase transmission powers, thus benefiting themselves. It shows that as the value of required SINR is increased, the transmission powers at the MCs are higher. This results in a better performance at the MCs. For low values of required SINRs, the MCs are restricted to using just enough power levels. In most cases, this reduces the transmission powers at the MCs to a considerable extent while attempting to maintain the SINR. This leaves possibility for SINR dropping below the requirements due to noise and interference which can be tolerated easier when using higher required SINR.

It overcomes disadvantages of the empirical formula approach, as the scheme is much closer to the ideal case of transmitting at "just enough" P_t. It does take into account all factors contributing to SINR and hence is successful in equalizing the SINR performance of all MCs. As seen, both the MC receivers as well as the Primary Receivers benefit as a result of this technique. Distance is not required to be measured and it can be implemented in the simplest systems.

4.5 Complete Interference Reduction Algorithm

The SINR Feedback Mechanism is one that is very close to achieving "just enough" Pt levels. Hence, this is the mechanism that is implemented in our CWMN system at the MCs. Algorithm 4.1 describes the interference reduction phase of the entire system, which reduces the interference by making use of two mechanisms: null positioning and adaptive power control at the MCs through the SINR Feedback Approach.

Lines 3 to 18 show steps executed by MCs served by the shifting MRs. Lines 13 to 15 shows the procedure executed if the MC is a receiver. When it sends an acknowledgement packet back to its transmitter, it piggybacks the SINR that is it facing as shown in line 14. If the MC is a transmitter, lines 7 through 11 are executed.

```
1:  Input: Primary Channels chosen by MRs, chosen_cr_chanel; direction of MC
    receiver, θ_RX; direction of primary Rxs, θ_PRI; default transmission power P_t
2:  Output: Transmission Parameters for the MC to reduce interference to pri system
3:  for MR = 1 to length(MR_set) do
4:      if shifting(MR) = 1 then
5:          for MC = 1 to no_of_MCs(MR)
6:              if MC_txing(MR,MC) = 1 then
7:                  Update θ_RX(MR,MC) and θ_PRI RX(MR,MC)
8:                  if piggy backed SINR from corresponding Rx is available then
9:                      update P_t(MR,MC) as per equation (4.8)
10:                 end if
11:                 beam_pattern(MR,MC) = smart_antenna(chosen_cr_channel(MR),
                                  P_t(MR, MC), θ_RX(MR,MC), θ_PRI RX(MR,MC))
12:             end if
13:             if MC_rxing(MR,MC) = 1 then
14:                 Piggyback SINR on acknowledgements to corresponding
                    transmitter
15:             end if
16:         end for
17:     end if
18: end for
```

Algorithm 4.1 - Interference Reduction

Line 11 shows the smart antennas beam formation with the specified parameters. The transmission is made on the chosen channel resulting from the Load Balancing algorithm 3.1. It transmits at a power level which starts at a default value, and is constantly updated to arrive at a just enough level. This is shown in lines 8 through 10 wherein if the MC received the SINR feedback from the receiver MC it updates its transmission power using relation 4.8. This regulates the transmission levels at the MCs so as to reduce the interference caused to the PU receivers. To account for the mobility of both the MCs and the PUs, the positions are updated at regular intervals and so are the angles at which they are located from the transmitting MC node as indicated by line 7. These angles are parameters in the transmission defined in line 11. The entire procedure is carried out continuously, over and over again.

4.6 Performance Evaluation

4.6.1 SINR Improvement in a Single Iteration

Figure 4.8 represents the SINRs corresponding to same set of four primary users analyzed in section 3.10.2. The SINRs at each of the four primary receivers is studied at a given instant where all communication links in consideration are active. The first three sets are the same as that depicted in Figure 3.8 representing cases of omni-directional, directional and smart antenna implementations at the MCs; all with equal Pt. The fourth set included in this figure corresponds to the case of the MCs in the secondary system implementing both smart antennas for spatial selectivity as well as adaptive power transmission using SINR Feedback.

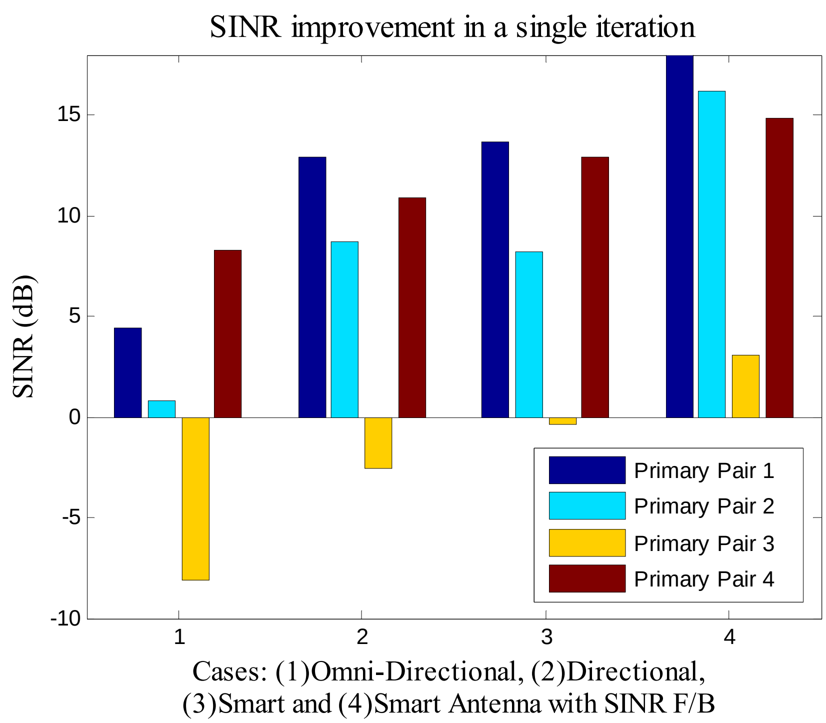


Figure 4.8 - SINR Improvement

It was seen earlier that PU receiver 3 still faced negative SINR, even after the incorporation of smart antenna transmissions at the MCs, and hence the PU pair was unable to sustain the communication because the distance between the Primary Tx and Rx is too large and the pair is more susceptible to the interference. However, after the SINR Feedback mechanism has been implemented in this setup, the MCs could eventually bring their operating power levels to a level low enough to increase the SINR at the primacy receiver 3 to satisfy the minimum 3dB requirement.

4.6.2 SINR PDF

The SINR Feedback Mechanism has been implemented over the same simulation of 10,000 random iterations in section 3.10.3 and compared the density function with the static P_t case. Four SINR pdf curves are plotted as shown in Figure 4.9, each over the SINRs experienced by the 40,000 primary receivers.

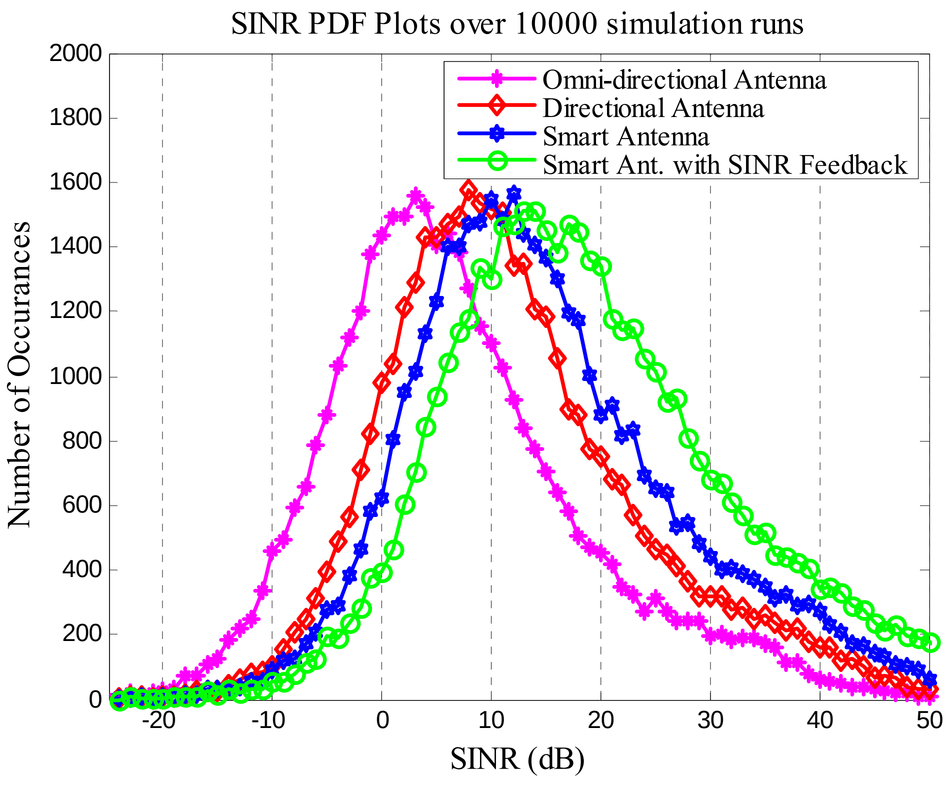


Figure 4.9 - SINR PDF

The first three curves correspond to the cases of MCs implementing static P_t through omni-directional, directional and smart antenna transmissions. The fourth pdf curve corresponds to the case when adaptive transmission powers were implemented through SINR Feedback, coupled with smart antenna transmissions.

In the case of smart antennas implemented over static P_t, the Gaussian curve of SINR pdf is centered around 10 dB, enabling 35,541 pairs to satisfy the SINR requirement. Incorporating SINR feedback implemented at the MCs, the SINR pdf curve at the PUs has been shifted to center around 14 dB. This provides a substantial 4dB increase in the average SINR at the PUs, a total of 11.5 dB gain over the omni-directional static P_t implementation. A total of 37,645 pairs (94% of the total number of PU pairs) satisfy the 3dB SINR requirement.

4.7 Summary

The previous chapter focused on obtaining substantial improvement in the interference reduction at the PUs using smart antennas in the CWMN MCs over the other implementations. In this chapter, we have proposed a dynamic transmission power control scheme at MCs planning to use PU's channels, and are coupled with the spatial selectivity methods of Chapter 3. This leads to an even better signal-to-noise-and-interference ratio (SINR) performance at the PUs. Our simulation confirms the effectiveness of our novel strategy over the static P_t scheme.

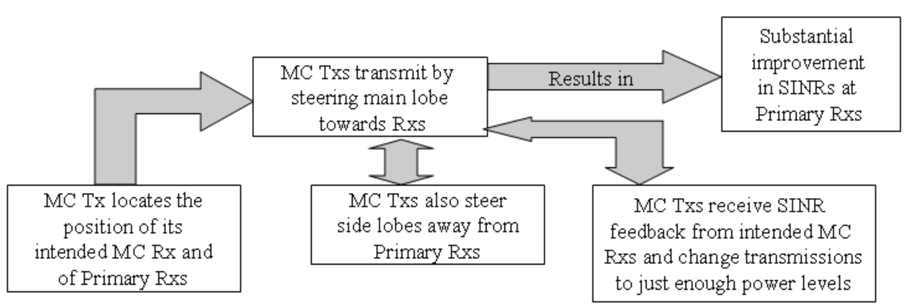


Figure 4.10 - Complete Schematic Diagram for Interference Reduction in CWMN

Chapter 5

5. A Probabilistic Approach to Spectrum Sensing

5.1 Introduction

The spectrum sensing procedures for the system setup discussed in section 3.4 have been described in section 3.10.1 for scenarios exploring different number of available PU channels and various densities of PU transmitter-receiver pairs. Figure 5.1 depicts a scenario with 32 available PU channels and multiple PU transmitter-receiver pairs in the vicinity of each cognitive mesh router (MR) serving a cluster of SU MCs. Similar to section 3.10.1, it shows the average powers sensed by all its associated MCs at various channels. In this case, the three PU pairs in the vicinity of the cluster occupy channels 7, 20 and 32, as indicated directly above the plot in figure 5.1. The average sensed power shows peaks at these corresponding channels. These peaks enable the MR to estimate the channels that the PUs occupy in its vicinity. Using this plot, it also decides which PU channel to change to. The MR planning to shift its operation instructs each of its associated MCs (SUs) to carry out a power measurement on each available PU channel, as described in the procedure that leads to this plot. This forces each MC to make a power measurement on each of the 32 available channels.

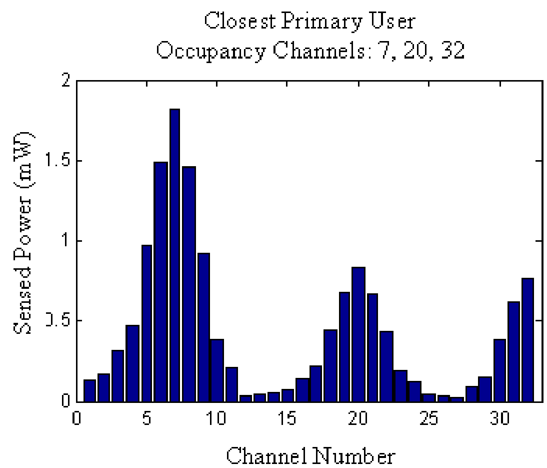


Figure 5.1 - Spectrum Sensing in a scenario comprising 32 available primary channels with 3 primary users in the vicinity of each MR

5.2 Limitations of Spectrum Sensing in our current implementation

Current implementation of spectrum sensing requires each MC (SU) to make power measurements on each available PU sub-band or the channel. This may be feasible if the number of available PU channels is small, in the range of 5 to 10. However, recent research focus has shifted to the unlicensed dynamic spectrum usage in television bands [18]**.** Hence, a practical scenario would involve availability of many sub-bands from the entire bands. For instance, some of the usable bands in the TV spectra consist of sub-bands between 470-570 MHz, 580-700 MHz and 700-800 MHz. A sub-band in the TV spectrum spans 6 MHz. Hence, each band afore-mentioned comprises of 16 to 20 sub-bands and there are multiple bands available. Thus, a scenario similar to Figure 5.1 is expected to prevail in actual practice. Hence, it would be highly impractical to analyze every sub-band before selecting one to shift the operating frequency. This ineffective use of resources would be more pronounced if the PU has a fast cycle of occupancy and release of its channel. In such cases, the effort needed in finding an optimum channel would be wasted if the PU wants to acquire the channel immediately after an SU shifts. Thus, it can be easily stated that the current implementation of spectrum sensing is highly inefficient. However, it is the most accurate way of determining the optimum channel which achieves the best SINR performance at the PUs, as every channel is analyzed by each associated MC (SU) and takes every possible geographical location into consideration.

5.3 Requirement from a better Approach

A new approach is expected to reduce the power measurement demand from the MCs (SUs). To improve the efficiency of the current spectrum sensing scenario, it is necessary to reduce the total number of sub-bands needed to be scanned before selecting one. Thus, the system must be able to judge which sub-bands have a higher likelihood of being unoccupied and scan them first. When operating frequency needs to be shifted, new approach must enable the system to obtain information about channels which have a higher likelihood of being unoccupied.

Essentially, the new approach would require some knowledge about how the PU system makes use of its available spectrum resources. With this knowledge, it is possible for the SUs to reduce the number of PU channels to be analyzed before one channel is selected.

5.4 Approach

In order to satisfy the requirements, we propose a probabilistic approach to spectrum sensing solution. All existing scenarios assume no knowledge of the PU system behavior regarding the channel access, while an ideal case requires complete knowledge of every PU channel's temporal occupancy. Through strategies proposed here, we aim to strike a balance between the two extremes, by using the fact that the usage of the sub-bands in the TV Spectrum is relatively periodic and predictable to some extent. The approach followed derives from the work of C. Ghosh et al., who stated in [5] that the probability of a sub-band being free during any duration can be estimated by observing the sub-band over multiple time durations. Hence, the approach involves making measurements on the sub-bands before changing operating frequency and utilizing past ‘historical’ data on channel access. Through these measurements, the occupancy probabilities of each sub-band at any given time can be calculated. Hence, in order to find a vacant sub-band, sub-bands with the least probability of being occupied should be scanned first. The authors, in [5], also propose the possibility of spectrum selection in cases with the availability of multiple bands which differ qualitatively in terms of the number of free sub-bands in each, which is also considered in this work.

5.5 Pre-operation Steps

The historical data collected about the PU band are the primary occupancy probabilities of each sub-band at any time and are obtained by performing measurements before the operation of the CWMN begins. This data-collection over each sub-band at different time intervals is referred to as the pre-operation step. Higher frequency of measurements conducted in this step would facilitate a higher resolution of probabilities. A per-minute resolution implies the probability of a sub-band being occupied for every minute of the day. The probability of occupancy is calculated as the fraction of time the sub-band is occupied in that minute during historical data collection. These probability sets are used in shifting an MR’s operating frequency by checking the sub-bands most likely expected to be unoccupied. It then selects the first sub-band that it finds vacant. Hence, the number of channels required to be scanned is drastically reduced by this mechanism.

5.6 Modeling PU's Occupancy Probabilities

Typically, PU's occupancy probabilities of the television spectrum consist of:

(i) Many sub-bands with a high probability of being free,

(ii) Many sub-bands with a low probability of being free, and

(iii) Few sub-bands with moderate probabilities of being free.

This is well characterized by a beta distribution with both parameters of α and β set to 0.5. Hence, in the simulations performed, such a distribution is used to generate the probabilities of PU's occupancy.

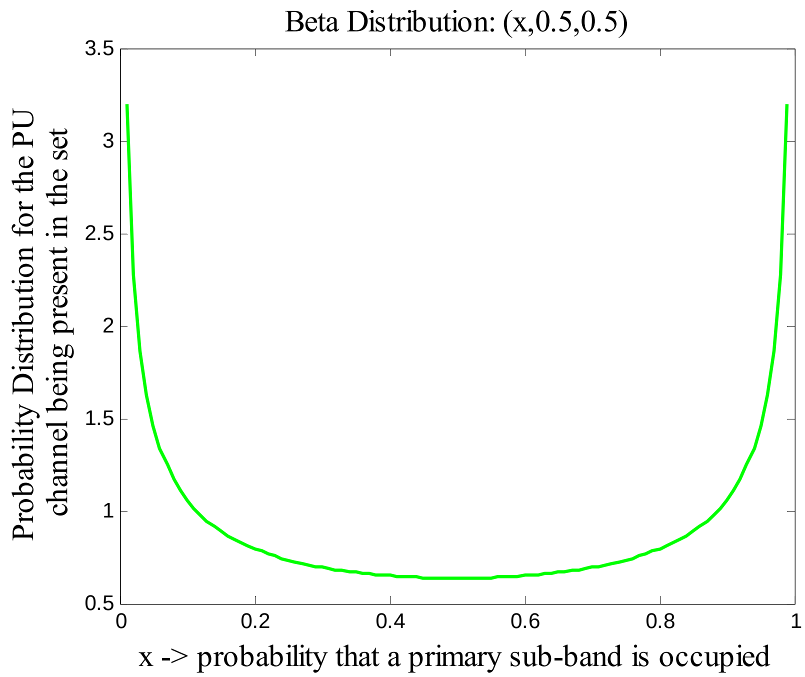


Figure 5.2 - Beta distribution to model Primary Occupancy Probabilities

Such a beta distribution with $\alpha = 0.5$ and $\beta = 0.5$ is plotted in Figure 5.2. The x-axis is the probability of a certain sub-band being occupied at a certain instant. The y-axis represents the distribution of such a channel being present in the set of PU channels. Hence, the peak at the beginning of the curve indicates that there are a high number of sub-bands which have a probability of less than 0.15 of being occupied. This verifies point (i) in the above list. The peak towards the end of the curve indicates that there are many sub-bands that have a probability of greater than 0.85 of being occupied. This verifies point (ii) in the above list. The lull in the rest of the distribution verifies point (iii) that there are only a few sub-bands having a moderate probability of being unoccupied.

5.6.1 Illustration of the Occupancy Probabilities Model

The following is a set of probabilities of primary occupancy corresponding to 20 available PU channels, generated using this beta distribution model. As expected, there are many sub-bands with high probabilities of being occupied and many with low probabilities.

Probability of occupancy set: (Defined by beta dist)

[0.0002, 0.9634, 0.4265, 0.6311, 0.4102, 0.2949, 0.9964, 0.2380, 0.0152, 0.9698, 0.0132, 0.8461, 0.1226, 0.8692, 0.5544, 0.9952, 0.8920, 0.9920, 0.9301, 0.9993]

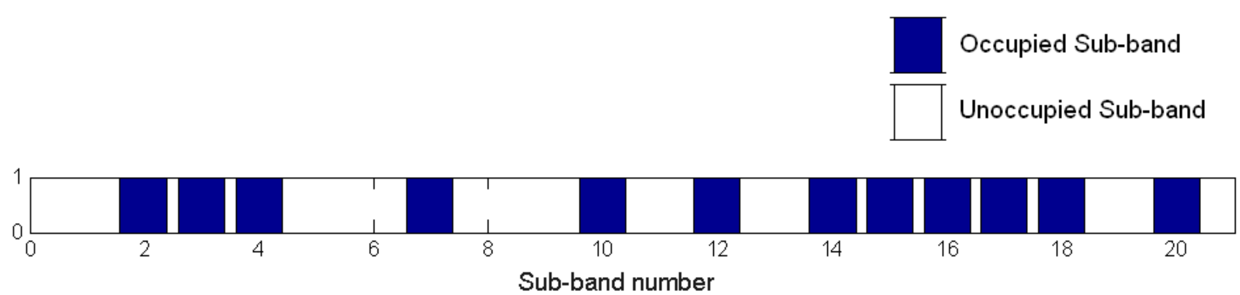


Figure 5.3 - Instance of Sub-band States generated using the Model

Figure 5.3 portrays an instance of the sub-band states of primary occupancy obtained using this set of probabilities. It is to be noted that this depicts just one instance and does not directly reflect the entire set of probabilities. For example, sub-band 19 is unoccupied in the depicted instance, even though it is listed as being occupied with a probability of 0.9301. In this instance, 8 of the 20 sub-bands are unoccupied.

5.7 Simulation Setup

Since the spectrum in this simulation is the TV band, a large area of 9 sq. Km (3Km x 3Km) is considered. The 700 – 820 MHz band is taken as the band of primary usage available for dynamic spectrum utilization by the SU system. A TV sub-band spans 6 MHz and hence implies the availability of 20 sub-bands in the bandwidth of 120 MHz under consideration. Up to 9 MRs may decide to shift the operating frequency of their clusters to the PU band of operation, one in each square Km of the area. PU receiver performance is analyzed in every square Km, with every PU receiver tuning randomly to one of the active sub-bands. The remaining operating parameters are the same as previously considered. MRs facing poor SINR performance make independent decisions in shifting operating frequency to the PU's band.

5.8 Schemes under consideration

5 schemes under are considered and compared to provide an optimum model of a probabilistic spectrum sensing approach:

1. FS - Full Sweep (Current Scheme)
   - Each cluster scans every single channel.
2. FF - First Found (Statistically same as Random Search)
   - Each cluster scans in order, until an empty sub-band is found.
3. PM - Probabilistic Model
   - Using the probabilities of PU occupancy, each cluster scans in the order of least probability of being occupied.
4. CPM - Co-operative Probabilistic Model
   - Uses probabilities but also updates a central database when choosing a sub-band.
5. SS-CPM - Spectrum Selection with CPM
   - Prior to CPM, an MR selects the best spectrum (band) based on the probability of most sub-bands being vacant.

5.8.1 FS - Full Sweep

This represents the current scheme implemented in the system, which requires the scanning of every single available channel. In such simulation, a cluster trying to shift operating frequency needs to analyze each of the 20 sub-bands before selecting one. An inherent disadvantage of this approach is that it is impractical to implement as it is excessively time consuming. However, it does take every channel's power measurement into account. Thus, it is the only mechanism by which the selection of the best channel and hence the best SINR performance at the PU's system can be guaranteed.

5.8.2 FF – First Found

As the name implies, this mechanism involves scanning one sub-band at a time in an order, until one that is vacant is found. Statistically, it is the same as scanning sub-bands in a random manner, as the occupancy model of the sub-bands varies the availability of sub-bands randomly.

Our simulation study analyzes the efficiency of the models in reducing the number of sub-bands to find an unoccupied sub-band. A single iteration of the model involves generation of primary occupancy states over the 20 sub-bands. Nine cluster sets proceed to find one unoccupied sub-band each, at different instances of time, with each cluster scanning the individual sub-bands iteratively until an unoccupied one is found. It is to be noted that when one cluster selects a sub-band for shifting, that sub-band becomes occupied. A subsequent cluster that scans it would detect it as unavailable and move on to the next one. The number of sub-bands scanned by each cluster to find a free sub-band is recorded.

The simulation is repeated over 1000 iterations and the density function for the number of sub-bands to be scanned to find an unoccupied sub-band is plotted in Figure 5.4. The probabilities of scanning from 1 to 10 sub-bands remain essentially constant and then begin to decrease. Such a poor performance is expected, as the cluster operates with no knowledge about the behavior of the PU's occupancy. Using the First Found mechanism, the average number of sub-bands that each cluster needs to scan is 9.9347.

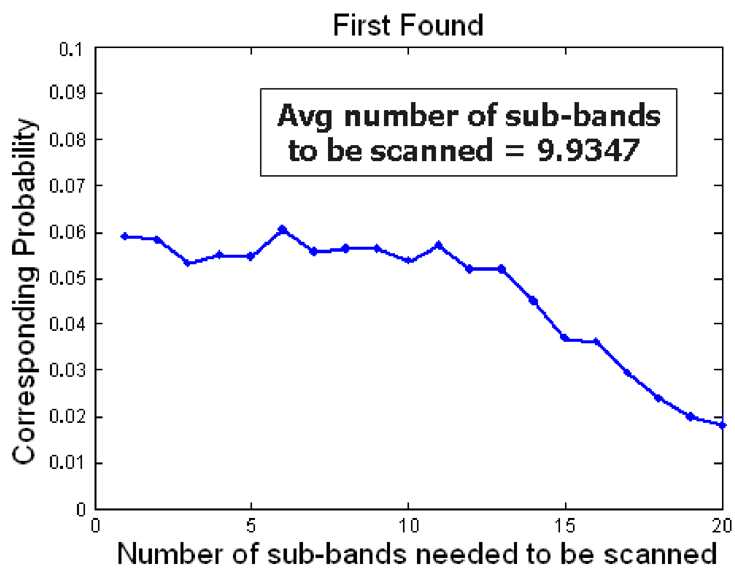


Figure 5.4 – FF PDF: Number of sub-bands to be scanned by a single cluster to find one available

In order that all clusters secure an unoccupied sub-band in a single iteration, at least 9 of the 20 sub-bands need to be unoccupied. This cannot be guaranteed or even expected due to random nature of the model. Hence, a significant number of the clusters do not succeed in finding an unoccupied sub-band.

To find any free sub-band, the First Found strategy can be implemented with no knowledge of PU behavior or the historical data. However, the knowledge of primary occupancy probabilities can be put to good use in reducing the number of sub-bands to be scanned considerably as will be shown in sections 5.8.3 through 5.8.5.

5.8.3 PM – Probabilistic Model

Using the knowledge of primary occupancy probabilities, this is a basic model to search for an unoccupied channel. The steps are relatively simple. An MR decides to shift operating frequency to PU's band when poor SINR performance begins to adversely affect its service to the associated MCs (SUs). From a central Gateway node or a base station, it obtains the probabilities of PU's occupancies over the sub-bands under consideration and each cluster scans the sub-bands in the order of the least probability of being occupied.

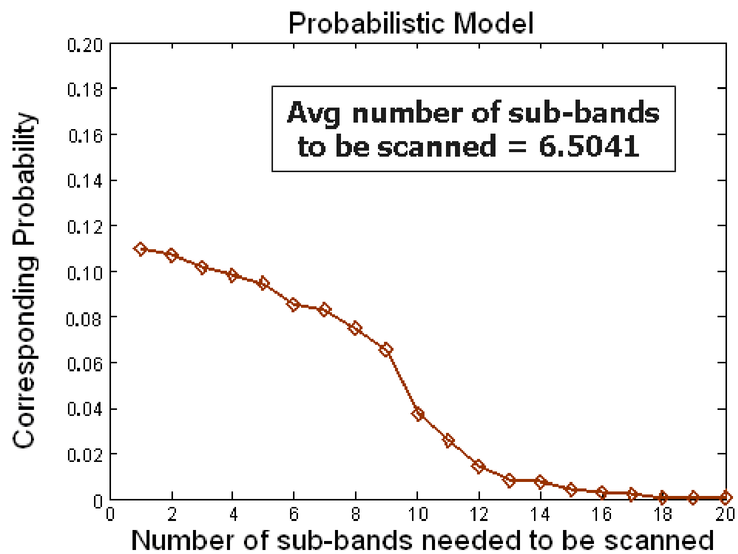


Figure 5.5 – PM PDF: Number of sub-bands to be scanned by a single cluster to find one available

Figure 5.5 illustrates the probability density function for the number of sub-bands to be scanned by a single cluster. This is obtained through the same simulation study performed over 1000 iterations of PU's occupancy states. It is seen that the probability of requiring to scan only 1 sub-band is the highest (11%), which suggests that this is the correct line of approach. However, it is not much larger than to scanning more than 1 sub-band and is attributed to lack of communication between the MRs, described below. The average number of sub-bands to be scanned using the probabilistic model is reduced to 6.5041.

This model has an inherent disadvantage that the selection of a channel is not communicated to other MRs. Subsequent MRs could still scan those sub-bands that have already been selected and this may increase the number of sub-bands to be scanned. For instance, if MR1 needs to shift its operating frequency to the PU band, it starts scanning in the order of least probability of primary occupancy. By this process, it first scans sub-band 7, finds it unoccupied and selects it. MR2 then needs to shift and starts scanning in the same order. Hence, it too would first scan sub-band 7. MR2 would find this sub-band to be occupied as MR1 has already selected it. It then continues scanning subsequent sub-bands. Thus, if MR2 receives information from MR1 about its selected channel, MR2 could avoid this unnecessary scan.

5.8.4 CPM - Co-operative Probabilistic Model

This model overcomes the inefficiency of PM by facilitating communication between the MRs about the selected sub-bands. This is done by directly updating the set of primary occupancy probabilities, while the initial steps remain the same. An MR that has poor SINR performance in its default band decides to shift its operating frequency to the PU's band. From the Gateway node, it obtains the probabilities of PU's occupancy at that instant. Using these probabilities, the cluster scans the sub-bands in the order of least probability of being occupied. When the MR selects the sub-band, it updates the central database of occupancy probabilities by replacing the probability corresponding to chosen sub-band with '1'. By doing so, an MR that subsequently sets out to find an unoccupied sub-band is aware that the previously selected sub-band is occupied. It then follows the general rules of operation and pushes these sub-bands to the very end of the scanning queue. Finally, when an MR releases a sub-band, it updates the probability value at the central database back to its original value.

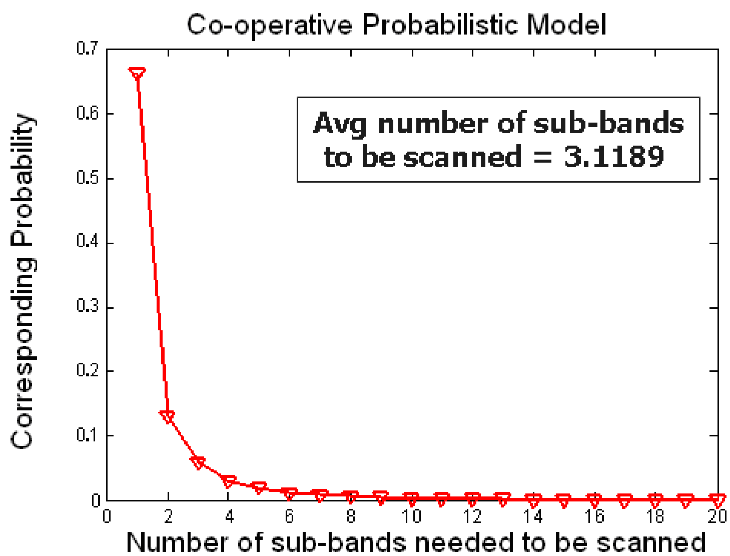


Figure 5.6 – CPM PDF: Number of sub-bands to be scanned by a single cluster to find one available

Figure 5.6 shows the probability density function of the number of sub-bands to be scanned by a single cluster in the CWMN using the CPM mechanism. A significant improvement is shown, with the probability of finding an unoccupied sub-band in a single scan being 66%. After this point, the pdf curve drops drastically. The probability values in the latter part of the curve are very close to 0, indicating that a free sub-band is most likely found using only a few scan attempts. Using CPM, the average number of sub-bands necessary to be analyzed is 3.1189. Hence, it is seen that the inefficiency of PM has been overcome and a close to ideal performance is attained.

5.8.5 SS-CPM – Spectrum Selection with Co-operative Probabilistic Model

The preceding section makes use of a probabilistic model for a single available spectrum extending from 700 to 820 MHz. However, as explained in section 5.2, there may be several such bands available for dynamic spectrum access. In this analysis, the three major TV spectral bands specified in section 5.2 are considered. Each band is defined by the same beta distribution with parameters $\alpha = 0.5$ and $\beta = 0.5$. Due to temporal independence, each band has a different number of sub-bands occupied at different times. By analyzing the probabilities of primary occupancies of sub-bands in each spectrum, the expected number of available sub-bands can be estimated. Hence, the best spectrum is estimated as the one with the most expected number of available sub-bands. A typical Co-operative Probabilistic Modeling procedure is then carried out on this selected spectrum.

PUs may sporadically occupy and vacate the sub-bands and it would be difficult for SUs to tune to multiple spectral bands in short spurts. Thus, in our work, after the selection of the best spectrum, the SU's operation in the PU's spectrum is limited to a single band. This facilitates ease of re-tuning and limits the number of bands to be scanned.

The steps carried out for spectrum selection before performing CPM are as follows. The probabilities of primary occupancy at that time for the three spectra are obtained by the MR that decides to shift operation from the Gateway node. The expected number of occupied sub-bands in one spectrum at that time in the spectrum is calculated as the sum of the probabilities of PU's occupancy for each of the 20 sub-bands in the spectrum. The spectrum which has the least expected number of occupied sub-bands is chosen for the MRs to shift the operating frequency.

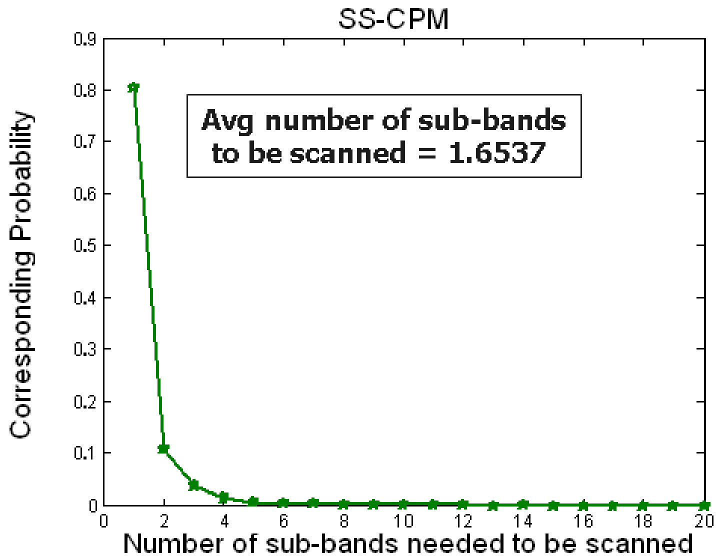


Figure 5.7 - SS-CPM PDF: Number of sub-bands to be scanned by a single cluster to find one available

Figure 5.7 shows the probability density function of the number of sub-bands needed to be scanned in the simulation experiment. It is seen that there is an 80% likelihood that the first sub-band scanned by an MR is available. This improvement is due to the selection of the best amongst three spectra that has the highest expected number of available sub-bands in each iteration. Using SS-CPM, the average number of sub-bands that need to be analyzed by an MR is 1.6537.

5.9 Performance Comparison between Single Spectrum and Spectrum Selection Scenarios

The first improvement when shifting from confinement to a single spectrum to selecting the best amongst three similarly distributed spectra is the number of sub-bands to be scanned. CPM shows that the average number of sub-bands required to be scanned is 3.1 and SS-CPM improved this figure to 1.6. Another difference is in terms of the number of clusters which require shift to a PU sub-band, but are unable to do so when all the sub-bands are occupied. As per the operation described, 9 clusters need to find an available sub-band in a single iteration.

This means that all the clusters may acquire an unoccupied sub-band only if at least 9 of the 20 sub-bands are unoccupied. Since the primary occupancy probabilities model is based on a random beta distribution, this cannot be guaranteed. Hence, a significant number of the clusters that need to find an unoccupied sub-band do not succeed.

Figure 5.8 quantifies the number of cases in which the required sub-bands are not found for the single spectrum mechanisms when 9 MRs needed to shift the operation per iteration. It relates to all the mechanisms described in sections 5.8.1 through 5.8.4.

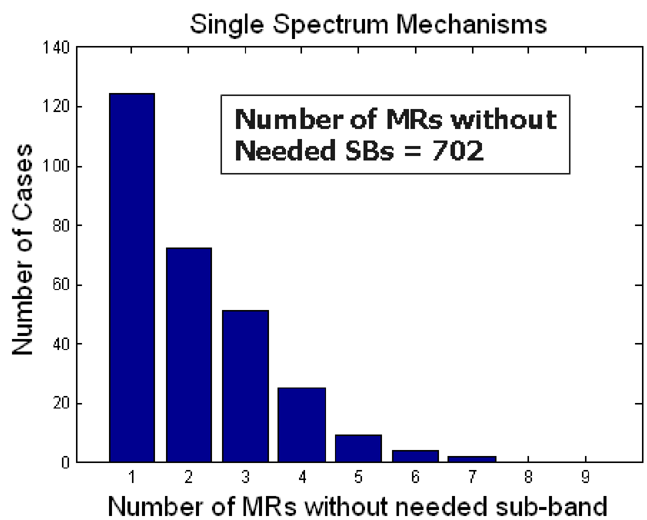


Figure 5.8 - Single Spectrum: Unavailability of sub-bands

As observed, out of the total 1000 iterations, 123 iterations have 1 of the 9 MRs failing to find an available PU sub-band. 73 iterations had 2 of the 9 MRs failing to find an available PU sub-band, and so on. A total of 702 MRs of the 9000 (7.8%) do not find a required PU sub-band.

Figure 5.9 represents a similar quantification of the unavailability of required PU sub-bands for the SS-CPM scenario with three bands, each distributed using the same beta model but temporally different. There is a visible improvement in the number of cases where no required sub-bands are available, as each iteration involves selecting the expected best of the three spectra at that time. A total 107 MRs out of 9000 (only 1.2%) that set out to find a PU's sub-band do not find one – a dramatic improvement over the single spectrum case.

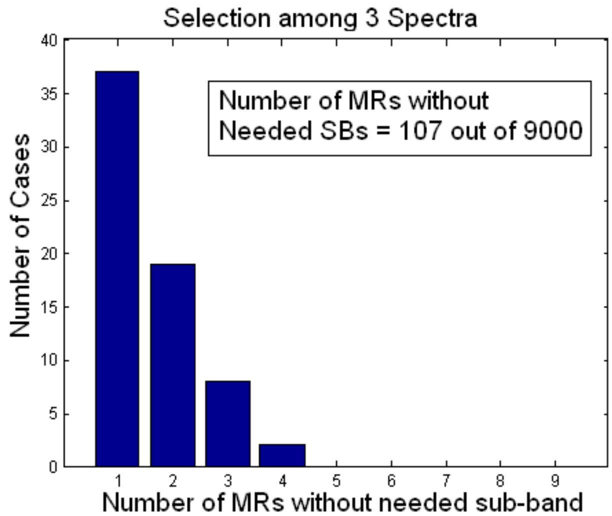


Figure 5.9 - Spectrum Selection: Unavailability of sub-bands

Figures 5.8 and 5.9 represent cases where each iteration involves 9 MRs trying to find available PU sub-bands among the total 20 sub-bands. Figures 5.10 and 5.11 show the improvement comparison between the single spectrum and spectrum selection scenarios for 5 to 20 MRs per iteration trying to shift. As in the previous analysis, the case of 9 MRs requiring a shift in the band of operation is reflected as 7.8% lacking for a single spectrum and 1.2% in the spectrum selection. The gain in using spectrum selection is significant in most cases; except in the latter cases of 16 to 20 MRs seeking to find a PU sub-band. For instance, if 20 MRs seek to shift operation, they require all the PU sub-bands to be unoccupied. In such cases where the secondary system seeks to acquire all or most of the available sub-bands, the improvement in performance asymptotically reaches 10%. This is because the increase in the number of available sub-bands between the two scenarios satisfies the same requirements. It essentially means an increase in the requirements with stagnant supply, which causes the saturation.

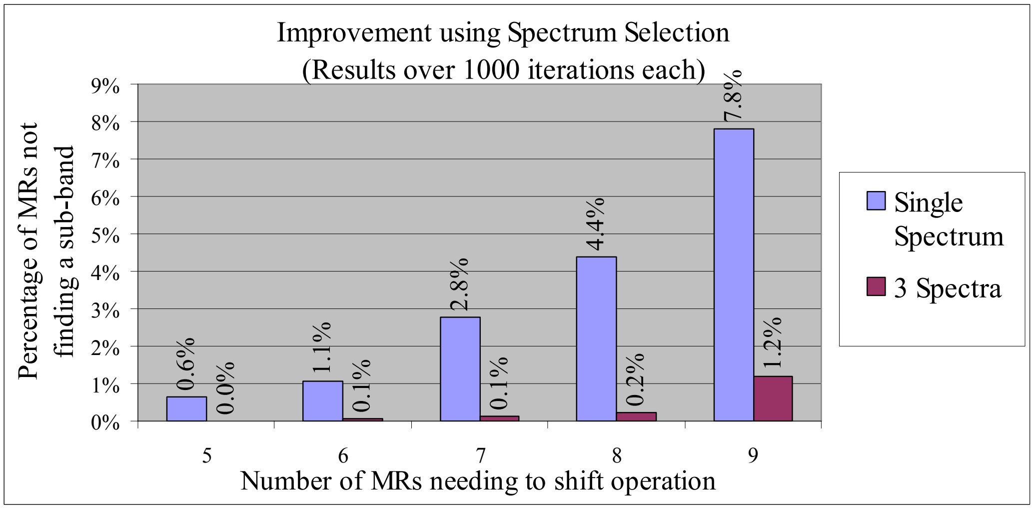


Figure 5.10 - Improvement using Spectrum Selection (5-9 MRs to shift)

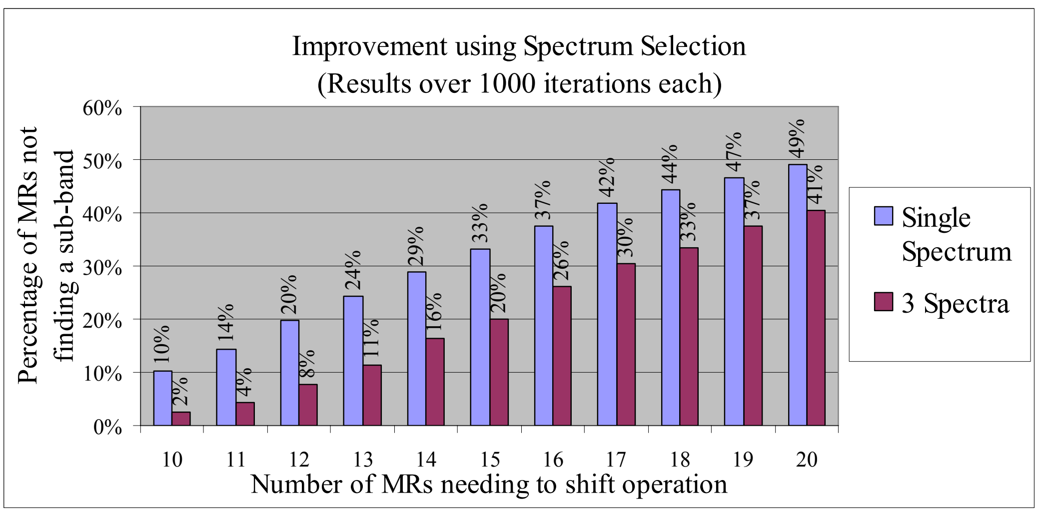


Figure 5.11 - Improvement using Spectrum Selection (10-20 MRs to shift)

5.10 The Trade-off

The probabilistic approach aims at finding an available sub-band as quickly as possible. The main advantages of using these procedures are an increased speed in the spectrum sensing and selection of an available PU sub-band. They cannot guarantee the selection of the best sub-band that causes the least interference to the PU receivers. Best SINR performance at the PUs can only be guaranteed if the MRs are forced to analyze every sub-band (which is the FS - Full Sweep scenario concluded to be impractical). Hence, a loss in SINR performance at the PUs is expected if scanning of every sub-band is avoided and is quantified in the analysis below.

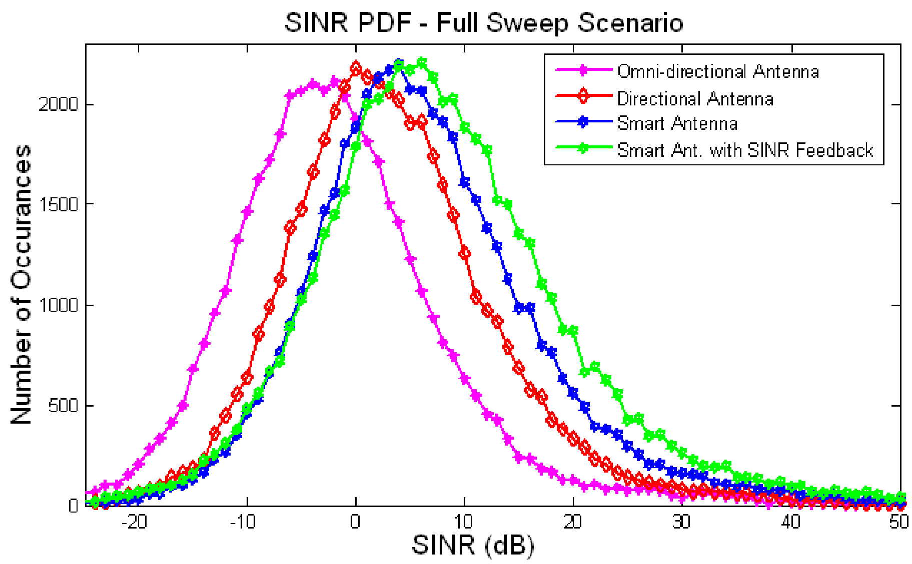


Figure 5.12 - Full Sweep Scenario: SINR PDF over 10,000 iterations

Figure 5.12 shows the SINR PDFs for the simulation scenario considered in this chapter. It involves operation in the TV band in the 9 sq. km. area with 9 MRs planning to shift operating frequencies into the PU's band. The differences in the simulation scenario cause a major difference in the PDF curves as compared to those depicted in Figure 4.9. The required SINR for detectability in Digital Video Broadcasting – Terrestrial television signals is -8 dB [19]. The PDFs are constructed over 10,000 iterations, in the same manner as discussed in 3.10.3. This figure shows the curves corresponding to the spectrum sensing scenario of the Full-Sweep mechanism. This case is expected to have the best operation in terms of the PU's SINR performance.

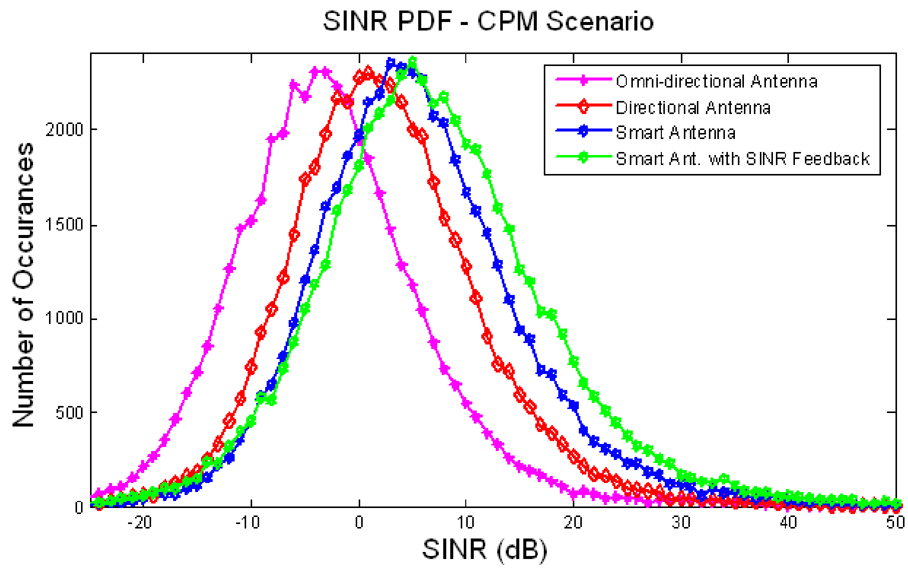


Figure 5.13 - CPM Scenario: SINR PDF over 10,000 iterations

Figure 5.13 gives similar SINR PDFs for the same simulation scenario, except that the spectrum sensing mechanism of the CWMN is shifted to the Co-operative Probabilistic Model (CPM). As expected, the SINR performance is marginally degraded. The mean SINR is 1.2 dB lower than the Full-Sweep scenario. This translates into a 32% increase in the interference on the linear Watts scale and is a negligible increase for a drastic change in the speed of the spectrum sensing mechanism.

5.11 Summary

In this chapter, we have proposed probabilistic models to improve the speed of spectrum sensing. The gain in the efficiency of finding an unoccupied sub-band is obtained by using historical data of PUs accessing their licensed bands. This gain comes at the cost of a negligible degradation in the SINR performance of the PUs.

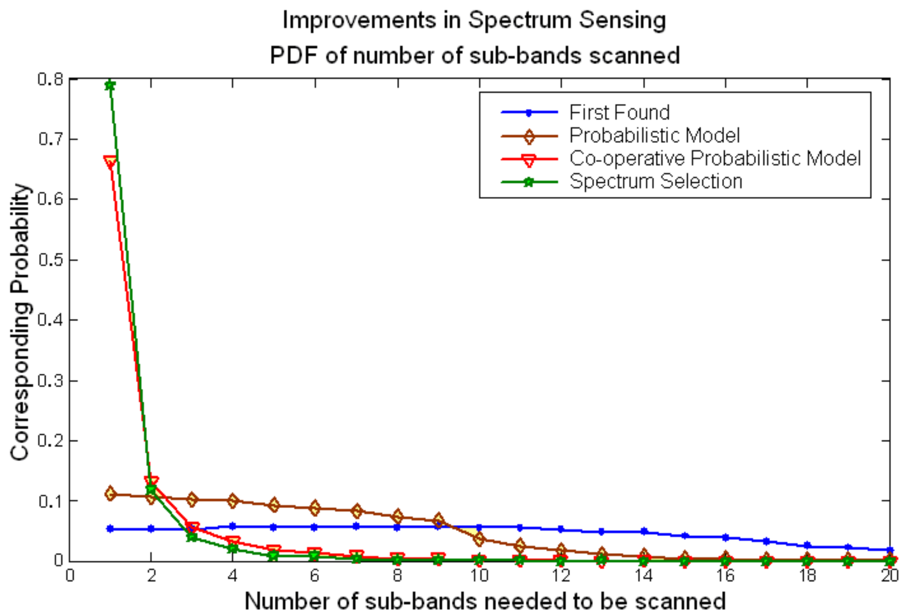


Figure 5.14 - PDF Comparison of No of sub-bands to be scanned

Figure 5.14 shows a comparison between each of the proposed probabilistic models of spectrum sensing, in terms of the PDFs of the number of sub-bands to be scanned by each MR shifting the operating frequency. The Spectrum Selection mechanism implemented with the Co-operative Probabilistic Model shows the best performance and is also reflected in Figure 5.15 by the average number of sub-bands to be scanned. This factor has been reduced from 20 to 1.6 by using the probabilistic models.

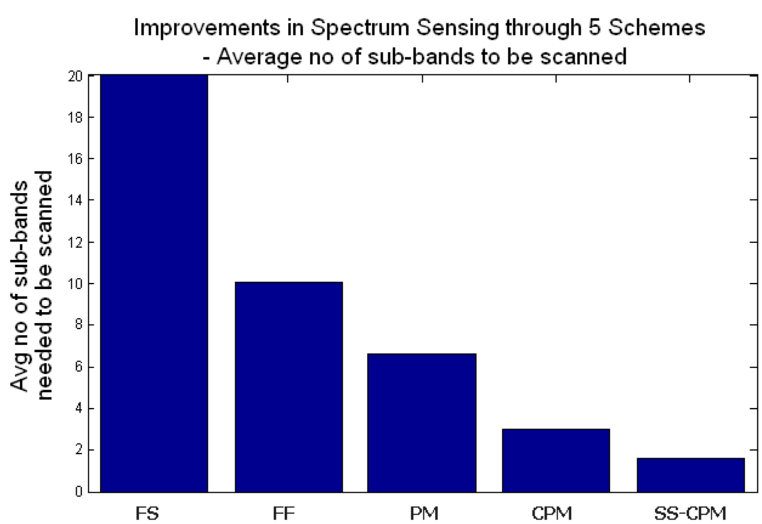


Figure 5.15 - Improvement in average number of sub-bands to be scanned

Chapter 6

6. Conclusion and Future Directions

6.1 Conclusion

In this thesis, we have incorporated smart antennas in CWMNs for reducing interference at PUs. First, based on power measurements made, we develop a load balancing strategy to switch an MR along with its constituent MCs to an unoccupied portion of licensed spectrum. We utilize a distributed spectrum sensing approach at the each target MR to select the best channel to switch to. An in-depth comparison of interference imposition on PUs while using omni-directional, directional, and smart antennas is made by analyzing their SINR performance. Our simulation results indicate a substantial improvement in the interference reduction using smart antennas over the others.

In the second part of this thesis, we have proposed two dynamic transmission power control schemes at the switched MCs to further improve the SINR at the PUs. We use an empirical formula that controls transmission power based on the distance to the intended receiver. This method is observed to be a trade-off in improving the SINR performance at the PUs at the cost of poorer SINR performance at the MCs itself. On the other hand, the SINR feedback mechanism is proved to be efficient in attaining just-enough transmission power levels at the MCs, and substantially improves the SINR performance at the PUs, and also improves the SINR performance at the secondary MCs. Our simulation results prove the effectiveness of our novel strategy over the fixed transmission power control scheme.

Finally, we propose probabilistic models to improve the efficiency of spectrum sensing. A significant reduction in the time required to find an unoccupied sub-band has been achieved by using historical data regarding the behavior of PUs about their access to licensed bands. A comparison between each of the proposed models of spectrum sensing has been made and a significant improvement over the default mechanism of scanning every sub-band is observed. The best performance is observed using the Spectrum Selection mechanism implemented with the Co-operative Probabilistic Model. The gain of improved efficiency in spectrum sensing comes at the cost of a negligible loss in SINR performance at the PUs.

6.2 Future Directions

The concepts presented in this thesis open interesting research directions. We have used spatial selectivity to reduce the interference caused to the PUs. Approaches of spatial diversity through Multiple Input Multiple Output (MIMO) systems may be explored and a comparison may be made between this alternative. These systems may have a higher degree of complexity in implementation and operation, but have few constraints and lesser dependency on the positioning system. MIMO systems may also prove to have smaller dimensions and hence may be practical to be incorporated in an actual system.

This thesis concentrates on shifting the frequency band of operation from ISM to the Television band. It may be interesting to study the possibility of similar dynamic channel allocation for a WMN in spectra such as the cellular band, primarily concentrated around 850 MHz and 1.9 GHz in the USA. The spectrum usage in these bands may be suitable for such secondary access, but are bound to have a significantly higher frequency in the PU occupancy and release cycles than those observed in the television bands. This presents challenges and may require a different strategy to be adopted for channel access, such as frequency hopping and spreading over a larger frequency to reduce the interference caused in a single sub-band. In such cellular networks, the opportunity for unlicensed dynamic access lies in the uplink portion of the spectrum. The base station terminal is less susceptible to the interference caused, as it is in control of the transmission powers of the mobile terminals [20].

Appendix

List of Publications:

1. V. R. Babu, C. Ghosh and D. P. Agrawal, "Enhancing Wireless Mesh Network Performance using Cognitive Radio with Smart Antenna," submitted to the *2009 IEEE Joint Workshop on Cognitive Wireless Networks and Systems - Cognitive Radio Networking, COGNET*, June 2009, Dresden, Germany.

2. C. Ghosh, V. R. Babu, D. P. Agrawal, *OFDMA for Cognitive Radio Networks*. Accepted book chapter for the book "OFDMA" to be published by Aurbach Publisher, USA.

3. V. R. Babu, C. Ghosh and D. P. Agrawal, "Smart Antennas in Cognitive Mesh Networks - A Two Tier Approach towards Spectral Efficiency" Poster presented at the *Ohio Graduate Students Symposium (OGSS)* 2008.

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