Distributed Beamforming for Cognitive Radio Networks

MSc Thesis Report

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By:

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Dedicated to my mother, Nunik Handayani

My brother Wisnu Prabowo and my sister Larasati Widyohening

Especially my late father Ir. H. Bambang Choliq

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LIST OF ACRONYMS AND ABREVIATIONS

AWGN – Additive White Gaussian Noise

BCDCP - Base station Controlled Dynamic Clustering Protocol

BF – Beamforming

CDF – Cumulative Distribution Function

CSI – Channel State Information

CR- Cognitive Radio

CDMA – Code Division Multiple Access

CH – Cluster Head

DB – Distributed Beamforming

DBF – Digital Beamforming

DOA – Direction of Arrival

FCC – Federal Communication Committee

GPS – Global Positioning System

HEED – Hybrid, Energy-Efficient Distributed

LEACH - Low Energy Adaptive Clustering Hierarchy

LEACH-C - Low Energy Adaptive Clustering Hierarchy Centralized

LU – Licensed Users

MIMO – Multi Input Multi Output

OFDM – Orthogonal Frequency Division Multiplexing

PSD – Power Spectral Density

PDF – Probability Distribution Function

QoS – Quality of Service

RU - Cognitive Radio Users

RF – Radio Frequency

SNR – Signal to Noise Ratio

SINR - Signal to Interference plus Noise Ratio

SDMA – Space Division Multiple Access

TDOA – Time Difference of Arrival

WSN – Wireless Sensor Networks

LIST OF MAJOR SYMBOLS

$G(\theta, \phi)$ –   Radiation Pattern of Antenna

$F(\theta, \phi)$ –   Array Factor

k –   Number of Antenna Array

w_k –   Weight of Each Antenna Array

d –   Distance Between Array Elements

d_0 –   Minimum distance between utilized nodes

λ –   Wavelength

$x_k(t)$ –   Received Signal at k element

$a(\theta_i)$ –   Steering Vector

$s_i(t)$ –   Signals from i-th source

(r_k, ψ_k) –   Realization of Node Location in Polar Coordinate

$(A_0, \phi_0, \theta_0).$ –   Destination Location in Spherical Coordinate

θ –   Elevation Direction

ϕ –   Azimuthal Direction

R –   Radius

$\tilde{R}$ –   Radius Normalized by lambda

d_k –   Euclidean Distance of Nodes

$P(\phi, \theta | r, \psi)$ –   Far-Field Beampattern

f_{r_k} –   PDF Function of r_k

f_{ψ_k}	–	PDF Function of ψ_k
$J_n(x)$	–	nth-order Bessel function of the first kind
σ^2	–	Standard Deviation
P_{av}	–	Average Power
ϕ_{av}^{3dB}	–	3-dB Beamwidth
N	–	Number of Nodes
t_0	–	CDF Requirement of LU
P_0	–	Threshold Power Requirement of LU
Δr_k	–	Distance Error
$\Delta \psi_k$	–	Direction Error
$\widehat{r_k}$	–	Node Distance With Error
$\widehat{\psi_k}$	–	Node Direction With Error
$\Delta \phi_0$	–	Destination Direction Error
$\hat{\phi}_0$	–	Destination Direction With Error

ABSTRACT

Cognitive radio (CR) is an approach with high potentials in the effort of battling spectrum scarcity, introduced by J. Mitola in the late 90's. It is capable of sensing the communication environment and adapting to it by changing its radio parameters. Beamforming technique allows the cognitive users to opportunistically access the licensed spectrum without interfering the licensed users by exploiting the spatial domain in the radio transmission. Distributed beamforming is a new concept to form communication beams by utilizing the distributed wireless nodes in order to transmit signals towards a distant destination. Applying distributed beamforming to the cognitive radio system gives the flexibility to the system, since the CR nodes are treated as virtual antenna arrays. CR also improves the lifespan of each node because the communication signal is generated in a distributed manner. This advantage of CR aligns with the principal of green communication which has the objective of less energy consumption.

Power efficiency area is a particular field of interest in the cognitive radio domain, where cognitive nodes are small battery-powered devices, distributed randomly in an area. Optimal number of nodes selection is proposed in this thesis to optimize the power usage in the implementation of distributed beamforming in cognitive radio networks. The selection is based on the requirements of the primary licensed user in order to guarantee the quality of service (QoS) of the licensed user's link. Recent works on the distributed beamforming field describe that the average beampattern shows a deterministic result and the mainlobe is independent of the particular node locations when the number of utilized nodes is considered as very large. However, for finite number of nodes, the beampattern does depend on the number of nodes and the way they are selected. In this thesis research, an approach is presented for deciding the number of nodes for distributed beamforming. Furthermore, several novel node selection algorithms such as Euclidean based, sector based, ring range, and circle range are proposed and their performances are studied in detail in this thesis work. In these entire schemes, the precise locations of distributed nodes of CR are needed. Further in this thesis, location errors of CR nodes and destination are taken into consideration. Its impact on the generated beampattern of the selected nodes is reported. The results show which of the proposed methods are more robust to the location information error of the CR nodes.

CHAPTER I

INTRODUCTION

I.1. **Definition of Problem**

In the modern era, there is a common believe that spectrum scarcity is happening at frequencies which can be used economically for wireless communication. This concept arises due to the heavy occupancy of frequency spectrum below 3 GHz which is caused by the ever growing demand for wireless services by the customers. This problem has placed a heavy burden to the resource allocation policy maker to accommodate between the demand and the available spectrum resources. However, according to the snapshot of spectrum usage in the urban area shown in figure I-1, we can see that there is actually very little usage on the licensed spectrum especially on the spectrum over 3 GHz. This fact is contradicting with the mindset of spectrum scarcity, since we can see that we have spectrum abundance.
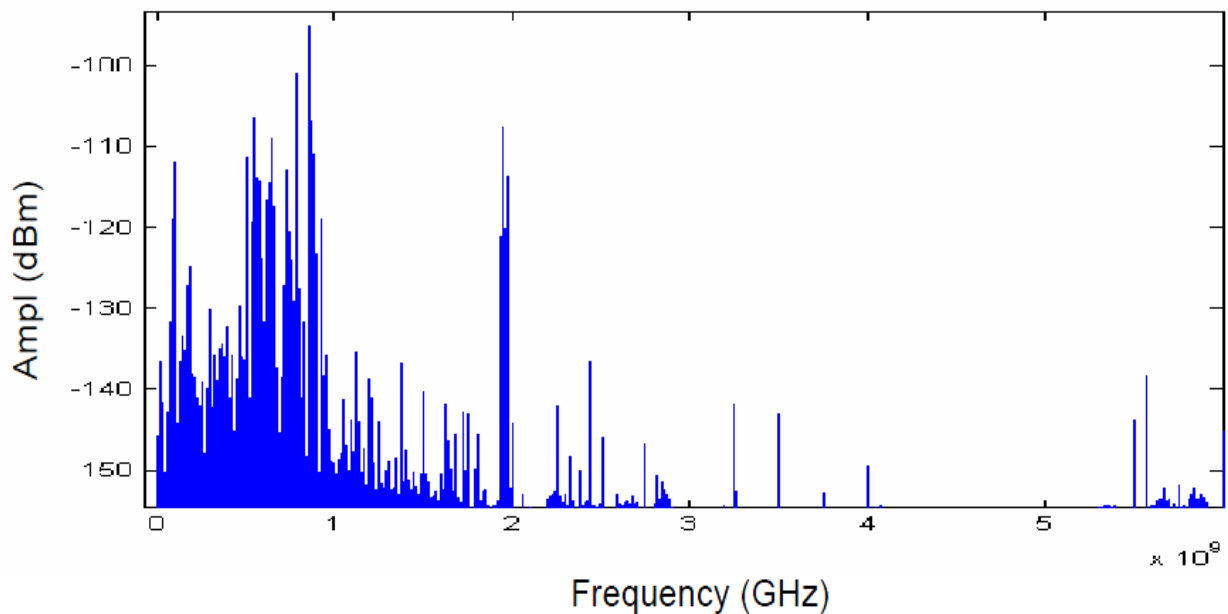
Figure I-1 Snapshot of spectrum utilization until 6 GHz in urban area [1]

The low level of spectrum usage also contradicts with the Federal Communication committee (FCC) spectrum allocations chart shown in figure I-2, which shows multiple allocations over the frequency bands. This contradiction shows that the spectrum scarcity is a product of the regulatory and licensing process by the authority and this condition indicates that new approach to the spectrum licensing is needed.
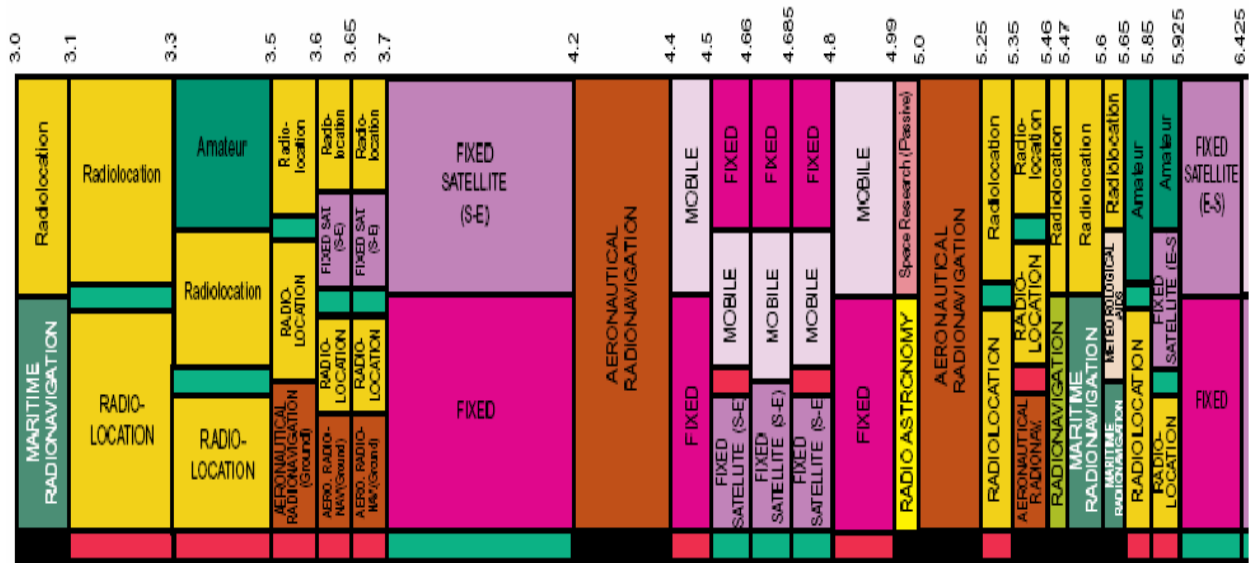
Figure I-2frequency allocation from 3-6 GHz [2]

An approach which is expected to solve the problem of spectrum scarcity is the **Cognitive Radio** (CR) [3] [4]. The CR system is developed to be able to sense the spectral environment over the available band and to use the unused spectrum as long as it doesn't interfere with the licensed user. The cognitive radio network usually consists of the primary or licensed users (LU) which has the priority and legality to access the communication spectrum, and the secondary or the cognitive radio users (RU) who use the spectrum only if they do not create interference to the primary users. This is where the cognitive radio technique is used by the secondary users to ensure non-interfering condition with the primary users. There are several ways to achieve the spectrum sharing with cognitive radio, such as space, time, frequency, and region. One of the strategies is to have the cognitive users to scan the spectrum and search for idleness, then access it when an unused slot is detected.

Beamforming is a well-known spatial filtering technique which can be used to direct the communication transmission or reception energy in the presence of noise and interference [5]. By using this technology, we can enable simultaneous communication links between the primary and secondary users with minimized or even total avoidance of interference. Beamforming allows the establishment of a communication link between the secondary users by exploiting the absence of a licensed user's communication link in a certain geographical location, also known as the spatial *spectrum holes*. The definition of *spectrum holes* is the frequency bands which are assigned to primary users, which at a particular time and specific geographical location are not used by them. The basic idea of beamforming in cognitive radio is to direct the radio signal to the direction of the destination, and to minimize the

2

transmission energy towards the primary users. This way we can suppress the interference caused by the secondary users to the primary users. In a multiple-antenna system, beamforming exploits channel knowledge in the transmitter to maximize the signal-to-noise ratio (SNR) at the receiver. Beamforming can also be used in the uplink or downlink in a multiuser system to maximize the signal-to-interference-noise ratio (SINR) to a specific user. However several challenges still exist if we want to implement beamforming into a cognitive radio system. One of the challenges is that beamforming can only be realized using arrays of antennas. In the case of traditional beamforming, we need arrays of antennas with a certain *weight* assigned to each of the array elements to direct the beam towards a specific direction. This condition will cause the implementation to be impractical due to the high cost of the antenna array establishment in each user compared to an isotropic antenna. Distributed beamforming is a solution to implement beamforming for a CR system without the necessity of adding extra infrastructure for the secondary users. We give an overview of a geometrical illustration of a cognitive radio system in figure I-3:
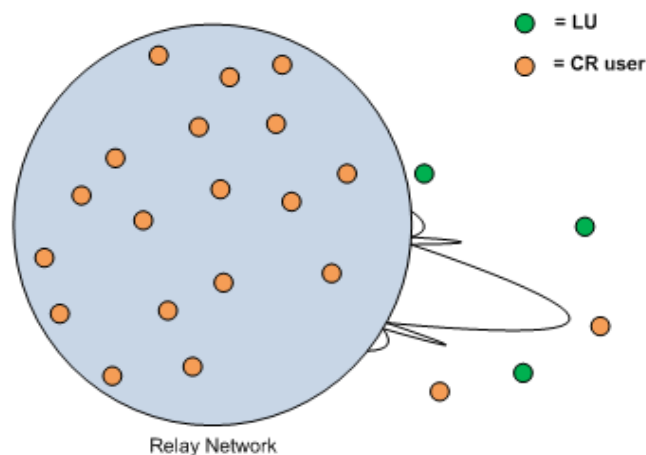
Figure I-3 Distributed beamforming

Distributed beamforming [6]-[8] has recently been introduced as a mean of establishing an energy-efficient and reliable communication link between the communicating relay nodes and toward distant nodes. One of the applications of distributed beamforming is the wireless sensor network, where a communication link is built between a low-powered sensor node and an access point which is located beyond the transmission range of each individual node. Distributed beamforming is a technique which could be the solution of implementing beamforming in the cognitive radio system. In the implementation of distributed beamforming in the cognitive radio, the secondary users are treated as virtual nodes contributing a small

amount of energy to establish a communication link towards the destination since the total transmit energy is divided among the contributing nodes. The cognitive radio user nodes act as independent antenna array elements which are used to form a focused beampattern toward the destination. Using the directivity of the beam, the secondary users can exploit the spatial spectrum hole in the radio environment to establish simultaneous communication links in the presence of a primary user. Distributed beamforming also enables the minimization of interference or even totally nullifies the interference towards the primary user.

I.2. **Motivation**

In the recent work on the field of distributed beamforming, it is shown that a large number of secondary user nodes contribute to form the communication link which will give a narrow main beam and low level of sidelobe. This result satisfies the purpose of implementing beamforming in cognitive radio, which is to establish a radio link between secondary users in the presence of licensed users. Since in the cognitive radio system there is a probability that the licensed users and secondary users are located close to each other, a narrow main beam and low sidelobe level is required. By utilizing a large number of secondary user nodes in the system, the energy consumption will also be large. On the other hand, utilizing insufficient number of nodes by itself will affect the communication beam. Using a smaller number of secondary nodes will give us a wider main beam and higher sidelobe level, which means a higher chance of interference around the direction of the destination and a higher interference level to the remaining angles. This fact leads to the question of how we can find an optimal number of nodes to form the radio beam by considering the green radio concept which supports the conservation of energy and the requirements of the communication link itself. In this thesis work we investigate the implementation of distributed beamforming in a cognitive radio system, where secondary users are trying to establish a communication link in the presence of primary users. Since the licensed users have the priority of occupying the radio frequency (RF) spectrum, the implementation of distributed beamforming by the secondary users will have to enable the communication link and minimize the interference to the existing licensed users. In this thesis an algorithm is proposed to optimally select the nodes for beamforming and for establishing a communication link between CR users. And finally we will present several node selection methods and compare them to take conclusion on the best node selection method under different circumstances.

I.3. **Objectives of Thesis Work**

The primary objectives of the project work are:

- To conduct a survey of literature on the implementation of distributed beamforming in cognitive radio.
- To establish an algorithm to find the optimal number of nodes for distributed beamforming in CR networks.
- To evaluate the effect of when a relatively small number of nodes is utilized for distributed beamforming in CR networks.
- Investigate several proposed node selection algorithms, and make a conclusion of which algorithm gives the best result under certain circumstances.

I.4. **Contribution of Thesis work**

This thesis work contributes to the field of distributed beamforming in cognitive radio network in a green communication manner. Since distributed beamforming is originally employed as an energy efficient scheme to cope with the long distance transmission problem, optimization of power consumption is of particular interest. The optimal node number selection algorithm is proposed for the sake of reducing the energy consumption of distributed beamforming when transmitting signals to a distance destination. Consequently the lifespan of the cognitive radio nodes is also extended.

Several node selection algorithms are presented in this thesis. The position of the nodes selected in the distributed beamforming affects the performance of the beampattern generated. Thus, the node selected for each case of distributed beamforming implementation is a particular interest. The results of the node selection algorithm are compared in several scenarios such as small, medium, and large number of nodes. The presence of a location error is also considered as a particular scenario. After the comparison, we can then decide which node selection algorithm gives better performance among the presented methods.

I.5. **Organization of Thesis Work**

The thesis work is organized as follows (figure I-4):

- In chapter 2 we give the basic principles of cognitive radio and how the system can be the solution of the spectrum scarcity. The theory of traditional beamforming and adaptive beamforming is presented in this chapter; we examine the properties of the

beamforming theory to get the basic idea of how to implement it to the cognitive radio network.

- In chapter 3 we present a theory of distributed beamforming, where we examine the properties of distributed beamforming, present the geometrical model, and review some of the recent works in the field.

- In chapter 4 we implement distributed beamforming in a cognitive radio system. The proposed method of optimal node number selection and the node selection are presented in this chapter. The node number selection method is based on the requirements of the licensed user and the statistical properties of the beampattern. The node selection methods which are based on the geographical location in the area will be presented and compared.

- In chapter 5 we present the simulation results of the proposed method and analyze the result. The results which will be presented are the conventional beampattern of the system, and the cumulative distribution function of the beampattern.

- In chapter 6 we draw conclusions from the work and give recommendations for future work.

Basic
Theory

Distributed beamforming in
cognitive radio
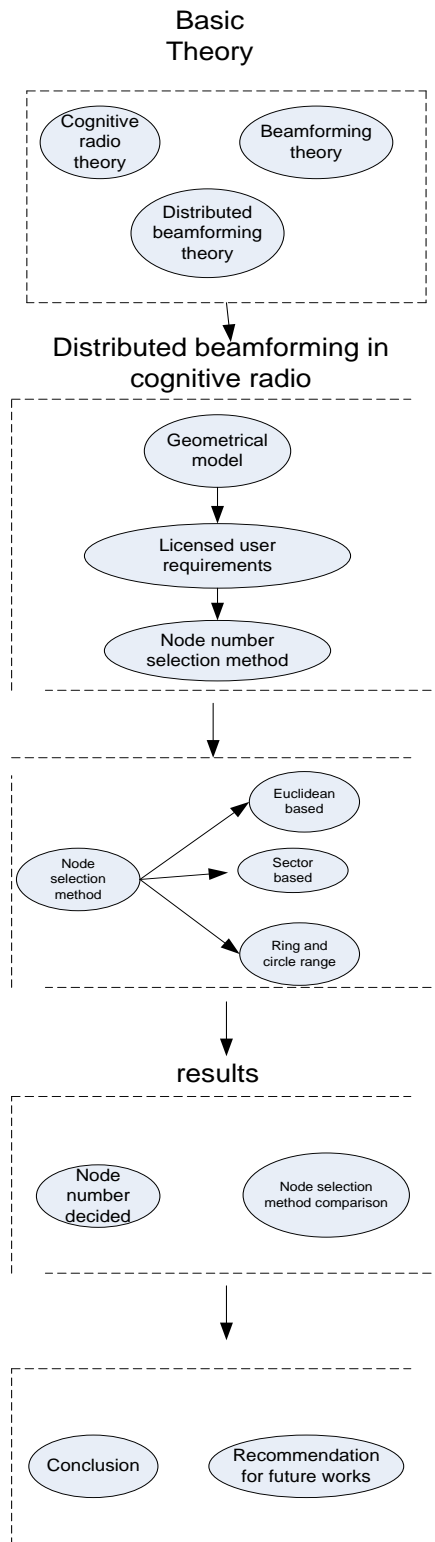
Figure I-4 Organization of thesis work

CHAPTER II

BACKGROUND THEORY

II.1. **Principles of Cognitive Radio**

Recent advances in wireless telecommunication technologies have sparked the ever growing wireless applications and services. This condition resulted in a burden which takes form of the spectrum scarcity. The electromagnetic radio spectrum is a natural resource whose usage in transmitting and receiving is controlled by the government. As mentioned in the previous chapter, it is concluded that the scarcity of electromagnetic spectrum is more due to inadequate access techniques rather than non-availability. This has resulted in major re-thinking in the regulation of electromagnetic spectrum usage by the government as well as the technology of spectrum access itself. Many researches have been deployed to overcome this problem, and one of the initiatives is the idea of Cognitive Radio (CR).

First of all, let us describe the condition of the under-utilized electromagnetic spectrum.

1. Some frequency bands in the spectrum are largely un-occupied most of the time.
2. Some of the frequency bands are partially occupied.
3. The remaining frequency bands are heavily occupied.

So we can say that there are frequency bands which are assigned to primary users, but at a particular time and specific geographical location, the bands are not used by the licensed users. This condition is referred as the *spectrum holes* [3]. The basic idea of CR is to improve the spectrum utilization by enabling the secondary users (unlicensed) to utilize the spectrum holes which are unoccupied by the primary users in a particular time and location. This is done in a way that the secondary users are invisible to the licensed users. In this scenario the licensed users are the mobile terminals and their associated base stations, which do not possess such intelligence. On the other hand, the secondary users should possess the capability of sensing the spectrum and use whatever available resources when they need them. At the same time, the secondary users must give up the utilized spectrum whenever a licensed user begins transmission.

In [3] Haykin described the CR as an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to

statistical variations in the incoming RF (radio frequency) stimuli by making corresponding changes in certain operating parameters in real-time with two primary objectives in mind:

- Highly reliable communications whenever and wherever needed;
- Efficient utilization of the radio spectrum.

Modulation scheme, transmit power, channel coding, and carrier frequency are examples of the parameters that can be exploited in CR.

II.1.1. **Cognitive Tasks**

The basic fundamental tasks of the system are: [4]

- *Spectrum Estimation*: is to gauge the radio spectrum scenario and perform radio scene analysis.
- *Channel State Estimation and Predictive Modeling:* is an accurate and timely channel state information (CSI) at the transmitter, and is important for accurate power control, prediction of channel capacity and scheduling.
- *System Reconfiguration*: based on the radio spectrum scenario and the channel state information, the system adapts the parameter.

The first and second tasks are done at the receiver side, and task 3 is done at the transmitter side. By interacting with the radio frequency environment, these tasks form a cognitive cycle (Figure II.1). The spectrum estimator senses the spectrum and detects the presence of spectrum holes, and interference region. The channel estimator measures the channel to get the channel state information. With the information derived from both the channel and spectrum estimation, the transmitter adapts the parameters based on the information. From the brief description, it is apparent that the cognitive module in both transmitter and receiver has to work in harmonious fashion. In order to maintain this condition, a feedback channel between the receiver and transmitter has to be established. Through this feedback channel, the receiver is enabled to send information on the performance of the link to the transmitter.
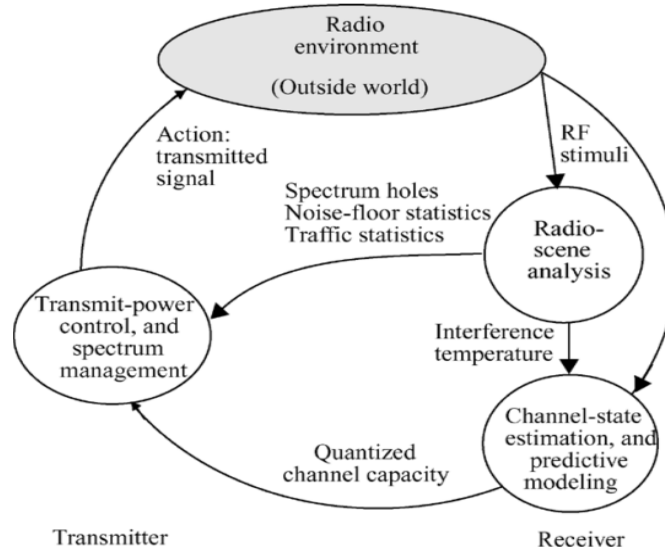
Figure II-1 Cognitive Radio Cycle [3]

II.1.2. **Spectrum Estimation**

The first task of the CR system is to measure the wireless environment over the electromagnetic frequency band and identify the occupied bands, and the spectrum holes. As described in the previous section, this task is done so that the secondary users can invisibly utilize the band without interfering with the licensed users. The main challenge of this task is in the identification and detection of primary user signals among the noisy radio environments. In this section we will give a brief description on a few spectrum sensing techniques available [4].

1. Pilot Detection using matched filter: when the information about the structure of licensed user signals are known (modulation scheme, pulse shape, band of operation (B), center frequency (f_c), etc.), pilot detection can be used to get the information about the presence or absence of a source. This technique of spectrum detection can be employed when the system is operating on a narrow-band pilot channel. Examples of such system are TV signals (with narrowband audio/video carriers), CDMA systems, OFDM   systems,   etc. The weakness of this method is that the CR needs a priori knowledge on the characteristics of the source, and a dedicated receiver for each of the licensed user. This method also very power consuming. The scheme of this technique is depicted in figure II-2.
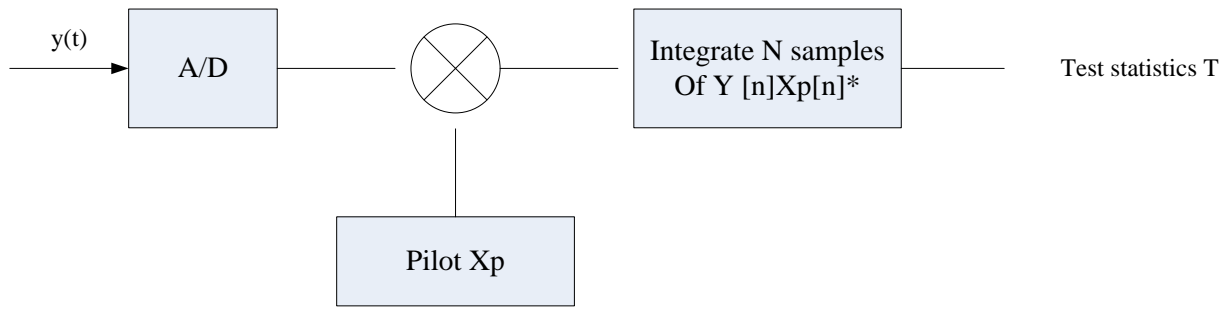
Figure II-2 Pilot detection using matched filter

2. Energy detection: this technique is simpler than the pilot detection using matched filter, because it is a non-coherent approach and does not need knowledge of pilot data. The implementation of this technique has found to be ineffective for narrowband signals and sine waves [10]. The disadvantage of this scheme is setting the threshold to determine whether a frequency sub-band is occupied or not, since the thresholds are susceptible to noise, fading, and in-band interference. The scheme of this technique is depicted in figure II-3.
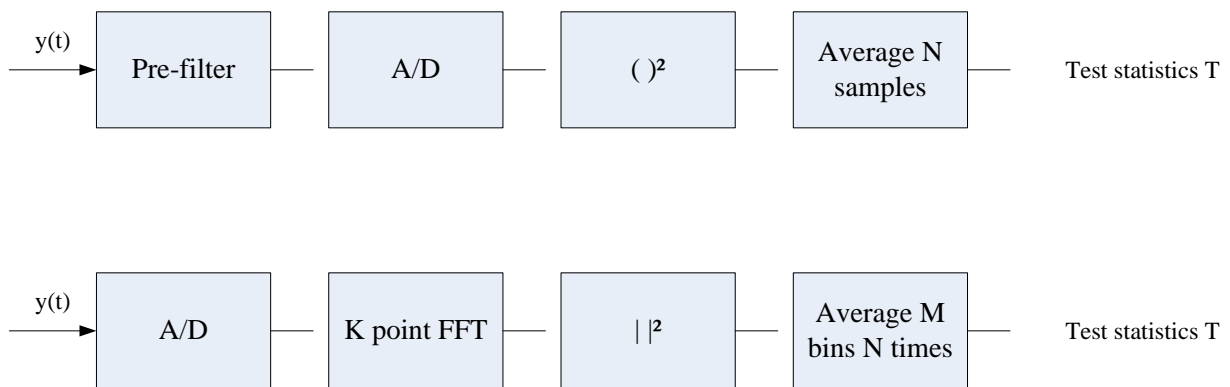
Figure II-3 Energy detector implementation

3. Cyclostationary feature detection: the feature detection technique exploits the inherent cyclostationary in modulated signals for the detection of a wireless source. The features which can be detected using this scheme are the number of signals, modulation types, symbol rates, and the presence of interference [11].

4. Wavelet based edge detection: in [12] wavelet based wideband spectrum sensing approach for dynamic spectrum sensing is discussed. The signal spectrum over a wide frequency band is decomposed into elementary building blocks of non-overlapping sub-bands that are well characterized by local irregularities in frequency. Then the entire wideband is modeled as a sequence of consecutive frequency sub-bands, where the power spectral characteristic is smooth within each sub-band but exhibit a discontinuous change between adjacent sub-bands. The information about the location

and intensities of the spectrum holes, and occupied bands are derived by considering the irregularities in power spectral density (PSD).

5. Cooperative spectrum sensing and beamforming: the techniques described in the previous section are local spectrum sensing technique where individual CR nodes (secondary users) survey the spectrum to gather the information. However, in the presence of shadowing or multipath-fading this scheme is proven futile [11]. Another approach is a group of CR systems to cooperate measuring the channel together. Every CR system broadcasts its snapshot of the spectrum to other units and a spectrum occupancy table is maintained to better regulate spectrum access. This way, the local measurements of the landscape can be combined and channel conditions such as multipath fading, shadowing, and local interference can be handled better.
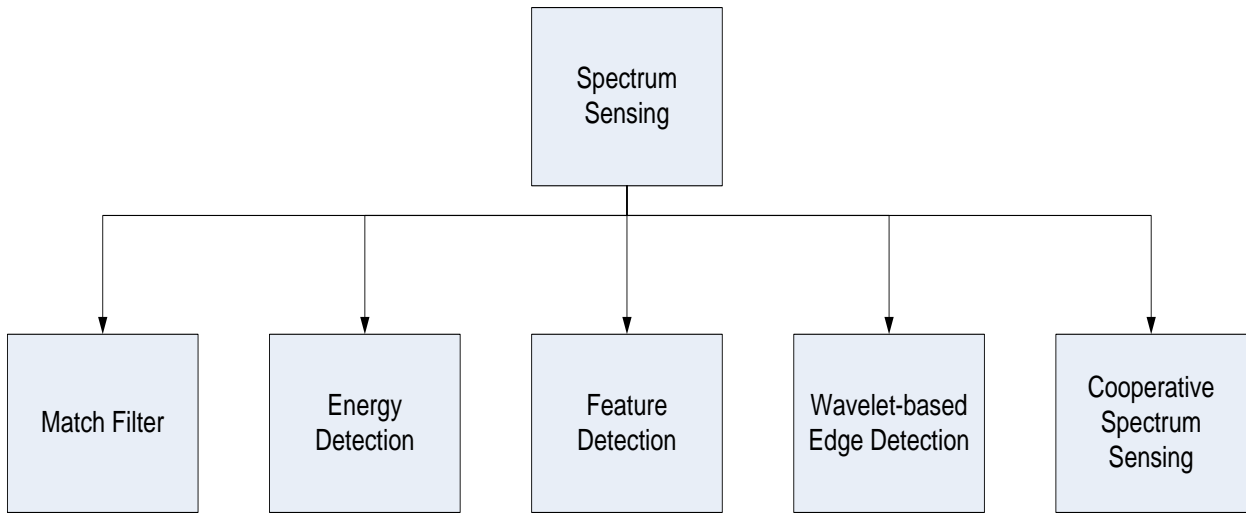
Figure II-4 Spectrum estimation schemes

II.1.3.   **Spectrum Adaptation**

After we derive the information about the spectrum holes and occupied spectrum, the next step of the cognitive cycle is to adapt the transmission system based on the condition of the RF environment. This is done in such a fashion that the CR setup blends seamlessly among the existing licensed users. The main goal of this task is to exploit the information about the RF environment to adapt its operation and access the un-utilized spectrum. The various spectrum adaptations can be broadly classified into three techniques:

1. Single carrier technique.
2. Multicarrier technique.

3. Beamforming as spatial based spectrum adaptation technique.

Figure II-5 describes the classification of the various spectrum adaptation techniques available. All of these techniques have the same goal, which is to facilitate the utilization of un-occupied spectrum to establish a communication link. MIMO (multi input multi output) in an added value transmission technique for both the single carrier and multi carrier spectrum adaptation techniques to enhance the QoS of the CR system.

The beamforming technique in spectrum adaptation is an effort to increase the utilization rate of a spectrum band via spatial diversity. When beamforming is applied to a communication link, it enables the spatial division multiple access (SDMA) where 2 communication links can be established at the same frequency band. Even though these communication links occur at the same band, they do not interfere with each other because the signals are occurring at different geographical locations. Thus, interference caused by other communication links are minimized or even nullified.

In this thesis work, we will concentrate on the beamforming schemes for the cognitive radio. Before we discuss even further about the beamforming technique for CR, we will present the theoretical background on the traditional digital beamforming in section II.2.
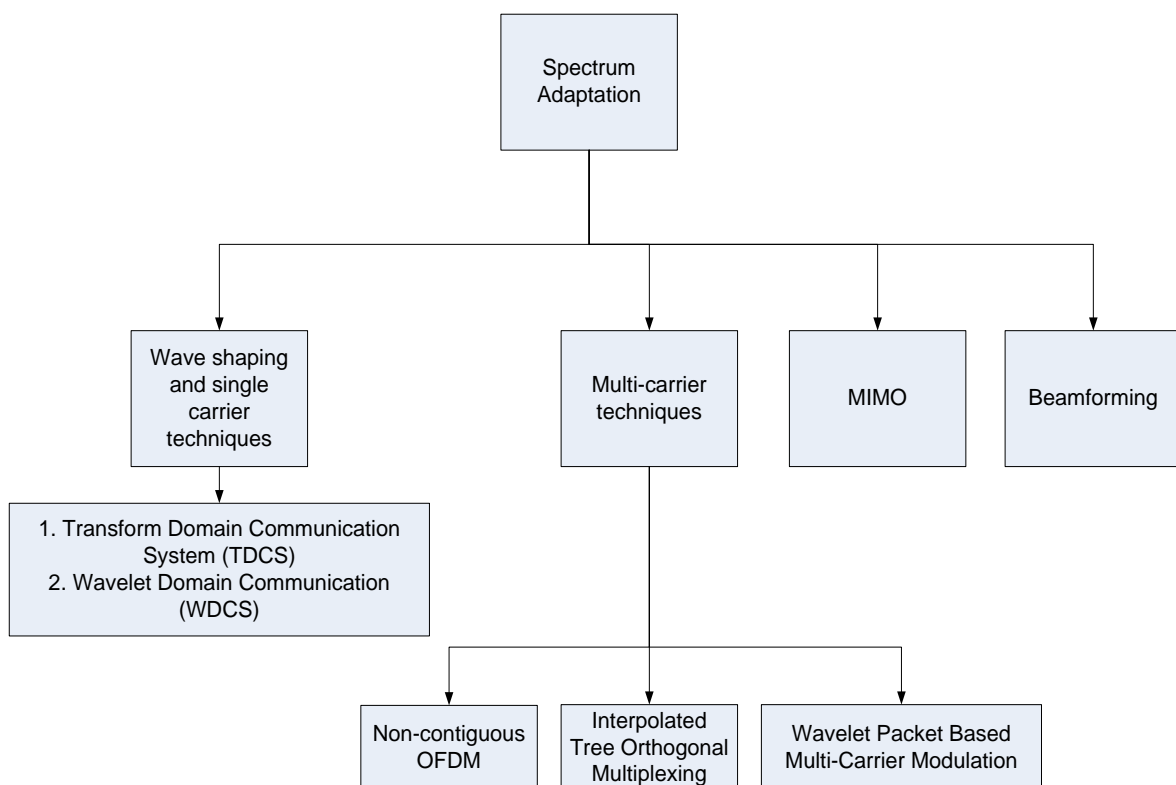
Figure II-5 Spectrum adaptation methods

II.2. **Principle of Beamforming**

The early concepts of beamforming were first developed in the 1960's for military applications in sonar and radar systems in order to remove unwanted noise from the output. It also has been studied in many areas such as seismology, and communications. Beamforming can be used for several purposes, such as signal detection, signal direction of arrival estimation (DOA), and enhancing a desired signal from its measurement corrupted by noise, competing sources, and reverberation. A beamformer is formulated as a spatial filter which operates on the outputs of a sensor array in order to form a desired beampattern. The signals induced at the different elements of an antenna array are combined to form a single output of the array. The operation of beamforming can be further decoupled into two sub-processes: synchronization and weight-and-sum. The synchronization process is to delay each of sensors output by a proper amount of time, so that the signal components coming from the desired direction are synchronized. The information needed for this process is the time difference of arrival (TDOA), which can be estimated from the array measurements using a time-delay estimation technique if it is not known *a-priori*. The next process is the weight-and-sum step. In this step the signals received from the antenna array are weighted and then added together to form one output. Both processes play an important role in controlling the array beampattern, the synchronization step determines and controls the steering direction, while the second process controls the beamwidth of the mainlobe and the characteristics of the sidelobes. Since the direction of the beampattern generated by the array antenna is defined by the weight of each antenna elements, most of the attention to beamforming is often paid to the second step on determining the weight coefficient for each array. In many applications, the weighting coefficients can be determined based on a pre-specified array beampattern, but it is usually more advantageous to estimate the coefficients in an adaptive manner based on the signal and noise characteristics. In the next section, we will give the basic of antenna arrays, and the basic theory of beamforming.

II.2.1. **Antenna Arrays**
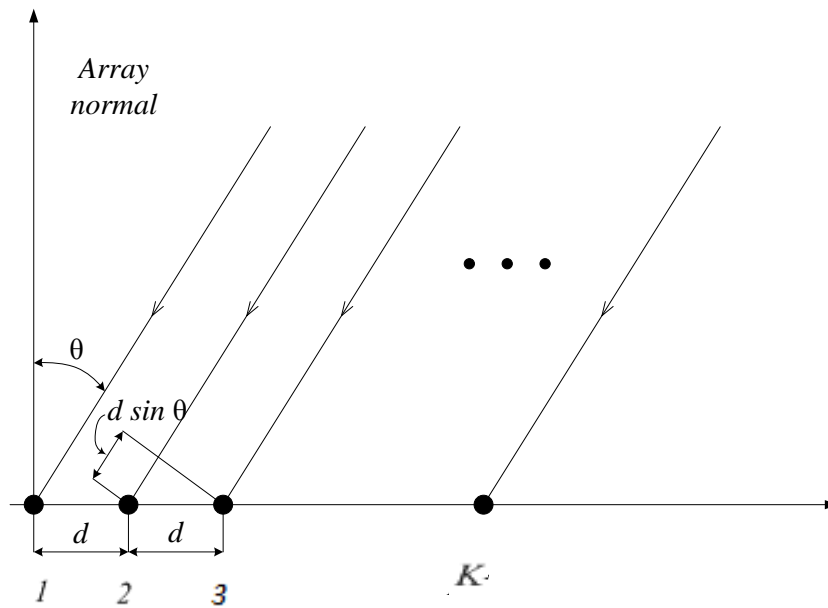
Figure II-6 Antenna array [5]

In order to understand the theory of beamforming, we provide a few definitions to describe antenna systems which will be used throughout the thesis work:

- Radiation pattern: the radiation pattern of an antenna is the relative distribution on the radiated power as a function of direction in space. Radiation pattern of an antenna is a product of the element pattern and the array factor.

$$G(\theta, \phi) = f(\theta, \phi)F(\theta, \phi) \qquad \text{II-1}$$

where $G(\theta, \phi)$ is the radiation pattern or also known as beampattern, $f(\theta, \phi)$ is the element pattern, and $F(\theta, \phi)$ is the array factor. θ is the azimuth angle, and ϕ is the elevation angle.

- Array factor $F(\theta, \phi)$: is the far-field radiation pattern of an array of isotropic radiating elements.

- Mainlobe: the main lobe of an antenna radiation pattern is the lobe containing the direction where the radiation power is at maximum level.

- Sidelobes: sidelobes are lobes of the antenna radiation pattern which do not constitute the mainlobe. The sidelobes allow the signals to be received in the undesired direction. However the sidelobes are un-avoidable.

- Beamwidth: the beamwidth of an antenna is the angular width of the mainlobe. The 3 dB beamwidth is the angular width between the points on the mainlobe which have half of the

radiation power of the mainlobe. The beamwidth is affected by the distance between the elements of the array.

Basically, a beamformer system consists of an array of antenna elements with independent receivers for individual antenna elements. In many applications of antennas where point-to-point communication is of interest, a highly directive antenna beam can be used to advantage. The directional beam can be realized by forming an array with a number of elemental radiators. As the directivity of the antenna increases, the gain also increases. At the receive end of the communication link, the increase in directivity means that the antenna receives less interference from the environment. First we look at the figure (II-6) to see the form of the antenna array. A uniformly spaced linear array in depicted with K identical isotropic elements, each element is weighted with a complex weight w_k with $k = 1,2,\cdots,K$, and the distance between the elements is denoted with d. If a wave impinges on the array at angle θ with respect to the array normal, the wavefront arrives at the element $k + 1$ sooner than at the element k, since the differential distance along the two ray paths is $d \sin \theta$. By setting the phase of the signal at the origin arbitrarily to zero, the phase lead of the signal at the element k relative to that at element 0 is $\varkappa\, k\, d\, \sin \theta$, where $\varkappa = \frac{2\pi}{\lambda}$ and λ = wave length.
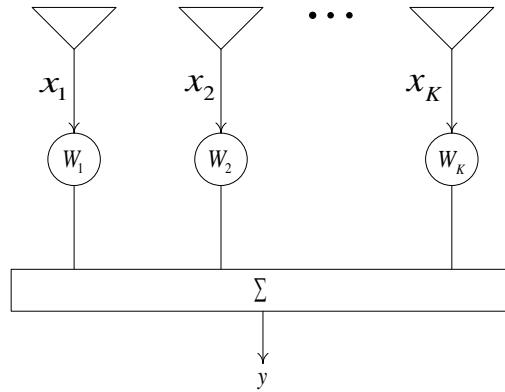
Figure II-7 Beamformer sums the weighted antenna element signals

The received signal at the kth element of the array antenna is given by:

$$x_k(t) = \sum_{i=1}^{j} \bar{a}(\theta_i)s_i(t) + n(t), \qquad t = 1,2,\dots,N \qquad \textbf{II-2}$$

Where t is the number of snapshots, $a(\theta_i)$ is the steering vector of the ith signal source in the direction of θ_i.

$$\bar{a}(\theta_i) = \left(1, e^{-j\varkappa d \ sin(\theta)}, \dots, e^{-j(K-1)\varkappa d \ sin(\theta_i)}\right)^T \qquad i = 1,2,\dots,j \qquad \textbf{II-3}$$

T is the vector transpose. $s_i(t) = 1,2,\dots,j$ are the signals from all sources, and $n(t)$is the additive white Gaussian noise (AWGN**).**

An example of a beampattern realization using the equation of array factor is given in figure II-8.
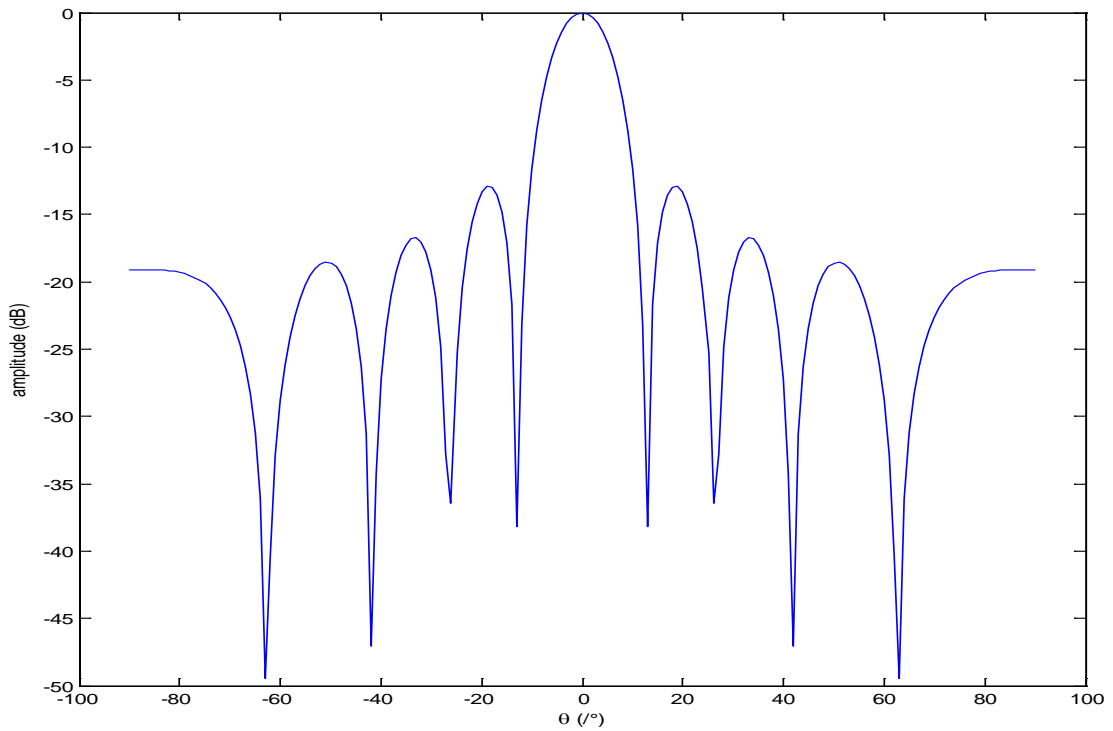
Figure II-8 Beampattern of 9 sensor array when $\theta = 0$, d = 6.25 cm, and $f = 2.4\ GHz$

II.2.2. **Benefits of Antenna Arrays**

After we describe the basic principle of beamforming and antenna arrays, in this section we will give an overview of the advantages we could achieve when implementing the antenna array system in mobile communication systems.

II.2.2.1. **Multiple Beams**

Using the antenna array, one is able to form multiple beams or sectorization by using multiple antennas at the base station in order to form beams that cover the whole cell site. For example, by dividing the antenna array into 3 sections, each covers 120° of area, resulting in the whole 360° coverage. The use of multiple beams results in co-channel interference reduction. In the

uplink scenario, the signal received from the mobile station constitutes interference at only two base stations, and additionally in only one sector. In the downlink scenario, the condition is quite similar. The difference is now the sectors which can interfere with the user in the central cell are the images of the interfering sectors on the uplink.
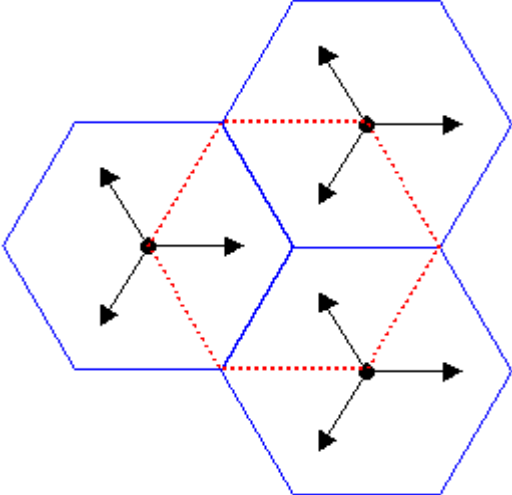
Figure II-9 Example of sectorization using antenna arrays

II.2.2.2. **Adaptive Beams**

The combined antenna array is used to find the location of each mobile using the DOA estimation technique, and then beams are formed based on the information gathered from the DOA estimation in order to cover different mobiles or groups of mobile stations. In conventional sectorization, the location of the beams is fixed, while the adaptive beamformer allows the beams to cover specific areas where the users are located.
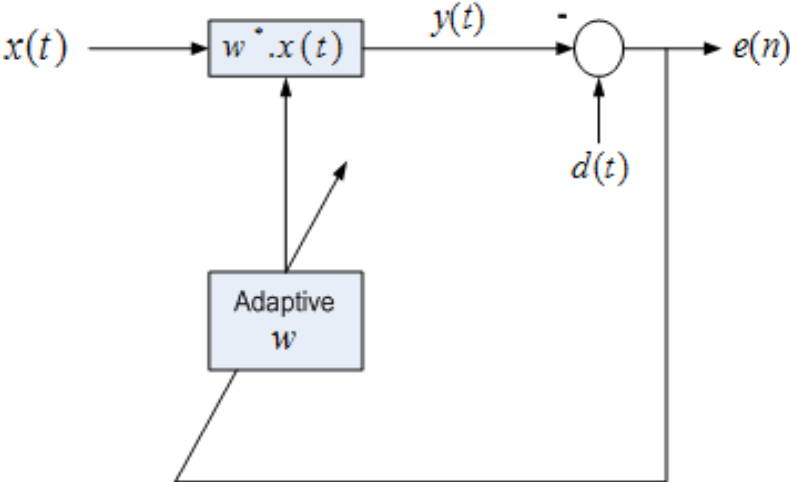
Figure II-10 Basic structure of adaptive filter in beamforming

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II.2.2.3. **Null Steering**

Null steering creates spatial radiation nulls towards certain directions, which will result in the absence of information. The realization of true nulls or zero responses is not possible due to practical considerations, such as the isolation of the radio frequency components. The null steering in the antenna response towards co-channel mobile users reduces the co-channel interference both on the uplink and the downlink.

II.2.2.4. **Reduction in Delay Spread and Multipath Fading**

Delay spread is caused by multipath propagation, where a desired signal arriving from different directions is delayed due to the different distances traveled. At the transmit side of an intelligent antenna equipped with a beamformer, it is able to focus the transmit energy to the desired location. This condition results in reduced multipath components and thus reduced delay spread. In receive mode, the antenna array is able to perform optimal combining after delay compensation of the multipath signals incident upon it. Those signals whose delays cannot be compensated or may be cancelled by the formation of nulls in their directions.

II.2.2.5. **Diversity scheme**

The most commonly used diversity scheme is switched diversity. In the scheme of switched diversity, the system switches between antennas, and only one antenna is used at a time. The switching criterion is often the loss of received signal level at the antenna being used. The switching may be performed at the RF stage, avoiding the need for a down-converter for each antenna. Another diversity scheme is the selection diversity where the criterion is based on the highest Signal-to-Noise ratio (SNR) at each branch on the receiver. Optimal combining process at the receiver processes the signals received from the antenna elements in ways that the contribution from unwanted co-channel sources is reduced, whilst enhancing the desired signal. With this spatial filtering and diversity scenario, we can conclude that by applying an antenna array we can increase the number of users on the same carrier frequency and timeslot. We also can call this scenario Space Division Multiple Access (SDMA).

II.2.2.6. **Reduction of Co-channel Interference**

When spatial filtering is enabled in a communication system in both the transmission and receiving end, co-channel interference will be reduced. When transmitting, the antenna is used to focus the radiated energy in order to form a highly directive beam in the area where the

receiver is located. This will result in less interference in the other directions, where the beam is not pointing. The co-channel interference can be further reduced by forming the null steering to the direction of other receivers or users. This scheme deliberately reduces the transmitted energy in the direction of co-channel receiver and hence requires prior knowledge of their positions.

II.2.2.7. Improvement of Capacity and Spectral efficiency

Spectral efficiency can be explained as the amount of traffic a given system with a certain spectral allocation could handle. An increase in the number of users in the mobile communications system without a loss of performance means that the spectral efficiency is increasing. Channel capacity refers to the maximum data rate a channel of a given bandwidth can sustain. An improved channel capacity leads to an ability to support more users of a specified data rate, implying a better spectral efficiency. The increased QoS (Quality of Service) due to the reduced co-channel interference and reduced multipath fading upon applying smart antenna may be exchanged for an increased number of users.

II.2.2.8. Increase in Transmission Efficiency

An antenna array has a high gain in the direction where the beam is pointing. This property may be exploited to extend the range of the transmission in a communication system, or even reducing the power required to form a communication link. In both uplink and downlink, application of antenna arrays will affect the threshold of minimum power required to send or receive a signal. This condition implies that less power is needed at both ends to send and receive the signals, low power rating electrical components can be used, and therefore lower cost is needed in the system.

II.3. Beamforming in Cognitive Radio

As described in the previous section, beamforming is a multi-access technique in mobile communications that takes the advantage of the position and angle of the other communication nodes. This technique can increase the range of the communication link, since the signal beam is concentrated only to the direction of the communication partner so that no energy is wasted to the other direction. Let us review the definition of cognitive radio in a communication system, where there are primary users which have the authority to utilize the spectrum in which they are licensed. In the real condition, where at a specific time and location the primary users are not utilizing the licensed spectrum, secondary users are trying

to communicate with each other by utilizing the unused spectrum in the range of the primary users. In case where no beamforming is implemented in a cognitive radio system, secondary users can only occupy the licensed spectrum when its location is far away from the licensed users so it will not interfere with the signal decoding process.
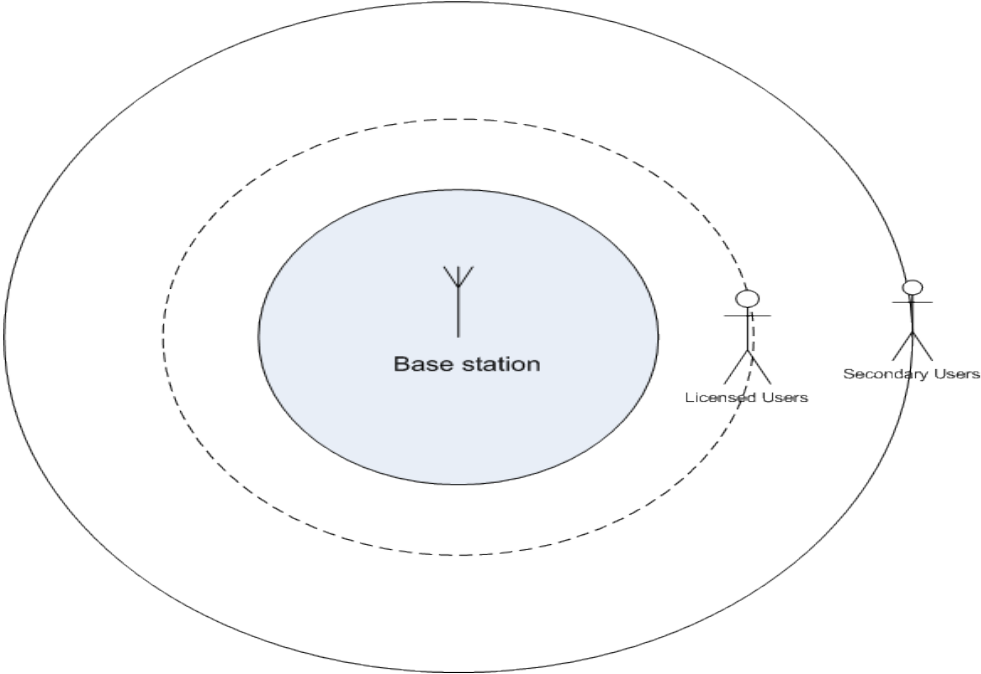
Figure II-11Communication link without beamforming

The scenario based on figure II-11 is that the base station transmits data to the licensed user which is located at the border of the decodability region (dashed line), the secondary users can only transmit communication signals outside the solid line in order to avoid interference with the licensed user. The shaded region in the center is the protected region where the signal decodability of the licensed user is guaranteed.
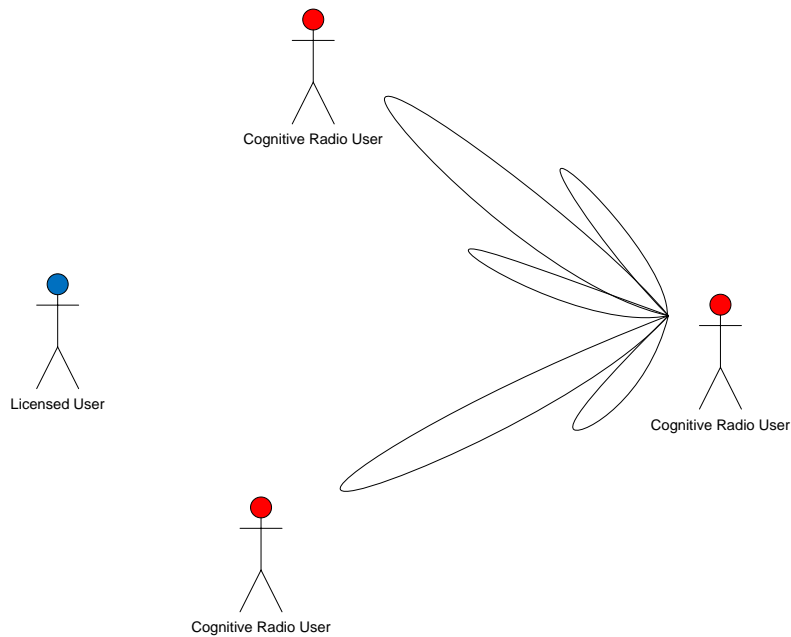
Figure II-12 CR with beamforming

Applying antenna arrays with a beamformer at each cognitive radio user will be the solution to cope with the spectrum utilization problem. Using the spatial filtering nature of the beamforming, one can direct its communication beam toward the destination and put nulls to the un-intended directions thus increasing the spectral efficiency of the communication system. This condition enables the cognitive radio users to exist among the licensed user and utilize the unused spectrum. The system will also have the benefits of applying an antenna array such as reduction in delay spread and multipath fading, co-channel interference reduction, etc.

Implementing the antenna array with beamformer in the cognitive radio system possesses several challenges. One of the challenges is the cost of implementing arrays of antennas to each of the cognitive radio users. This will result in a highly ineffective implementation since one of the benefits we are trying to achieve through this implementation is cost reduction. Recent development in the attempt of implementing beamforming in cognitive radio system is the Distributed Beamforming (DB)

Applying distributed beamforming in cognitive radio gives the advantages of array antennas such as SDMA and frequency re-use. Applying distributed beamforming in a cognitive radio network also enhances the coverage and energy efficiency of the system. In this system, cognitive radio nodes are collaborating to form a communication beam towards distant cognitive nodes which originally cannot be covered by a single node. Since the nodes are

collaborating together to form the beam, the total energy consumption is also divided between the nodes, thus reducing the power consumption of each node and prolonging the utilization time of the nodes. More on the distributed beamforming will be presented in the next chapter.

CHAPTER III

DISTRIBUTED BEAMFORMING

III.1. **Introduction**

One of the most challenging issues in wireless communications is how to cope with the reduction of SNR at the receiver. The reduction or increasing of the SNR is mostly caused by the noise and other phenomena such as path loss, shadowing, and multipath fading. As mentioned in the previous section, beamforming is one of the techniques that can be used to battle the multipath fading. Let us assume a transmitter with geometrically separated multiple antennas. When the same signal is transmitted from the separated antennas, even without multipath, the instantaneous power of the received signal can vary depending on the geometrical locations of the transmit antennas and the receive antennas. In other words, by doing so, the transmitter artificially creates multipath fading. When we look from a different perspective, if the transmitter has the a priori knowledge of the direction of the receiver, it is possible for the transmitter to send a signal such that the SNR of the intended receiver is maximized in that direction. This can be done by manipulating the signals sent from each of the antenna elements, so that their signals are added coherently at the receiver.

In many ad-hoc wireless networks, communication nodes which are battery-driven are more likely to be equipped with a single antenna. Based on this assumption, we are unable to implement beamforming in such wireless network. Adding an array of antennas to a battery powered mobile terminal will affect its lifespan, since more antenna elements are used. The idea which emerges from this condition is when there are nearby users who want to transmit data to the distant receiver, it would be much more efficient if they cooperate and share the transmitted data a priori. The transmission process has to be done in a synchronous fashion between the transmitting nodes, so that the compound data received at each destination is also synchronized. By appropriately setting the initial phase of the transmitting signals of each user, they can also cooperatively perform beamforming, assuming the other users or communication nodes as virtual antennas. This is the basic idea of *Distributed Beamforming* (DB).

From the description above, we can define distributed beamforming as a beamforming process done by the communication nodes or users of a network which are treated as virtual

array antennas in a distributed manner. To further understand the basic idea of distributed beamforming, let us look at figure below:
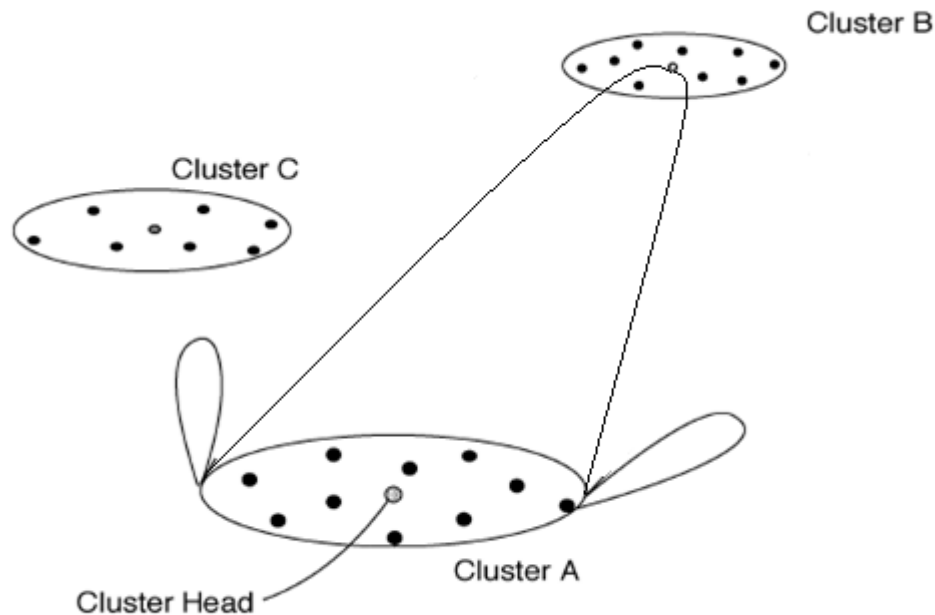
Figure III-1 Distributed Beamforming example [6]

The network users which are divided into clusters are located randomly by nature in a disk - shaped planar with a certain radius, which is why the beamforming must be performed in distributed manner. Such beamforming is often referred to as distributed beamforming. The earlier deployment of the distributed beamforming is in the field of wireless sensor networks, where sensor nodes are distributed nearby, and each collecting their own data. The sensor nodes form a cluster and transmit to the same destination cluster (depicted in figure III-1). Since the sensor nodes in the wireless sensor network have to be small and inexpensive, we can assume that they are equipped with only a single antenna.

Distributed beamforming techniques possess several challenges, two of the main challenges are how to share each message efficiently and how to perform synchronization among the cooperative users. If nearby sensor nodes that are trying to cooperatively transmit a signal to distant nodes share their information a priori, it is possible to form a beam in the intended direction. This particular scenario is often referred to as collaborative beamforming as all of the nodes in the cluster collaboratively send their shared messages to the same direction. By looking at this implementation scenario, the feasibility of precise synchronization and accurate channel estimation is a critical issue. In principle, distributed beamforming is formed

by manipulating the initial phase of synchronized transmitted signals with an identical message. This is possible only if the antenna elements (in this case, the network users) are synchronous and the channel impulse response is known at the transmitter [14]. A recent development of the synchronization process is described in [15]. The author presents two scenarios for nodes synchronization, namely the closed-loop and open-loop scenario.

In the closed-loop scenario, each node must have a precise knowledge of its relative location to the destination. The destination sends a beacon signal to the collaborative nodes, and then the nodes are synchronizing their initial phase accordingly. This scenario of synchronization is similar to self-phasing arrays. Since all the nodes and the remote receiver have to operate in a synchronous manner, they must share an identical clock. An outer clock such as global positioning system should be implemented in order to apply this scenario.
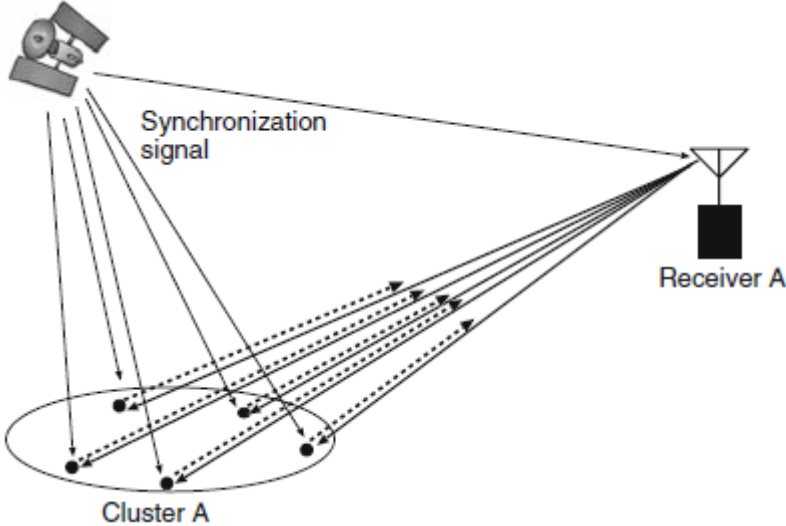
Figure III-2 Closed-loop scenario [16]

In the open-loop scenario, we assume that all nodes within the cluster acquire their relative locations from the beacon of a nearby reference point or cluster head. In this scenario, since the acquisition of precise knowledge is not realistic, the effects of a location estimation ambiguity among sensors on the beampattern may be of particular interest. This scenario is useful in the case of the network has receivers in multiple directions.
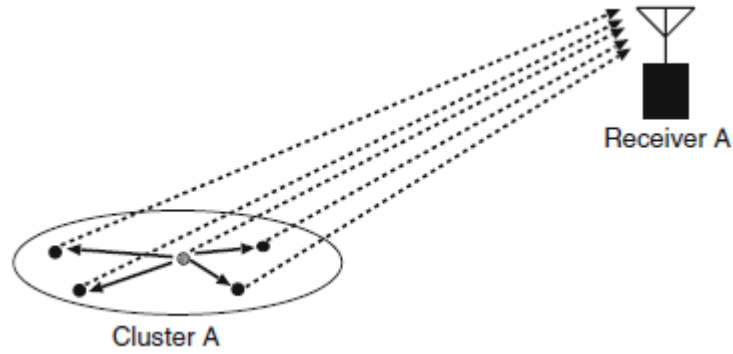
Figure III-3 Open-loop scenario [16]

Another issue is the result of the beamforming itself. One of the main advantages of beamforming is the enabling of SDMA (space division multiple access) which is already described in chapter 2. In order to do this, the main beam produced by the distributed beamforming has to be narrow and the sidelobes have to be low in order to avoid severe interference with the other communicating nodes. In this thesis work, we investigate the beampattern produced by the distributed beamforming in the presence of other nearby nodes.

III.2. **System Model**
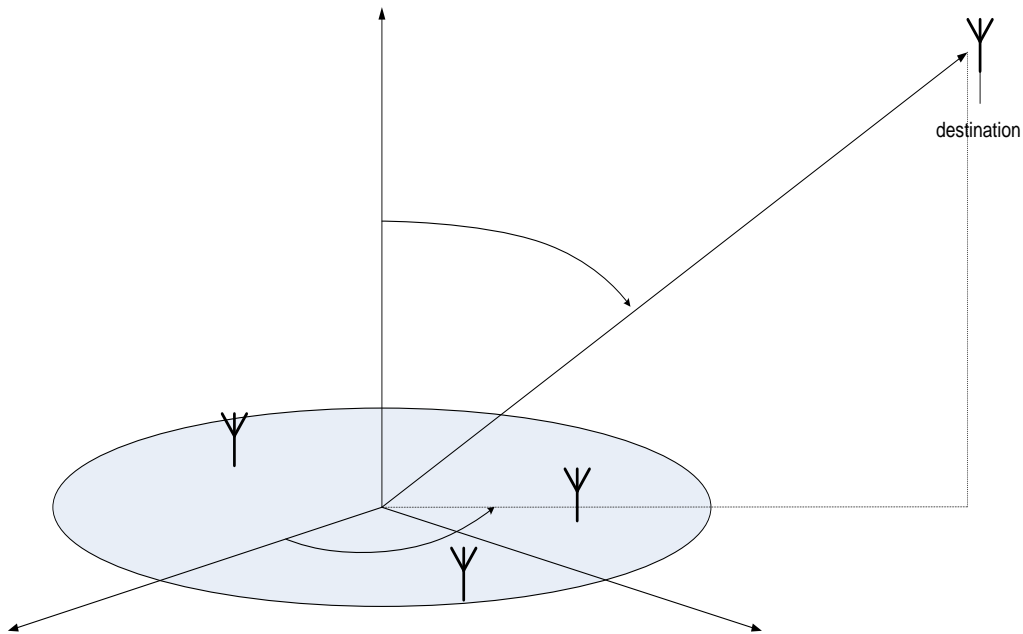
Figure III-4 Geometrical location of the nodes

Figure III-4 illustrates the geometrical configuration of the distributed nodes and destination. All of the nodes (virtual antenna elements) are assumed to be located in the $x - y$ plane, thus form a planar array. The location of the nodes is presented in polar coordinates, and thus the

location of the kth node is denoted by (r_k, ψ_k), and the destination is given in spherical coordinates as (A_0, ϕ_0, θ_0). The angle $\theta \in [0, \pi]$ denotes the elevation direction, and the angle $\phi \in [0, 2\pi)$ denotes the azimuthal direction. R is the radius of the plane normalized by the wavelength.

In this thesis work, we make several assumptions:

1. The location of each node is chosen randomly following a uniform distribution within a radius R.
2. Each node is equipped with a single ideal isotropic antenna.
3. There are no reflections or scattering, thus there is no multipath fading or shadowing.
4. The nodes are sufficiently separated so no antenna coupling occurrs.
5. All nodes transmit identical energies, and the path losses of all nodes are also identical. Thus it can be treated as the framework of phased arrays.
6. No mutual coupling between different antennas and cognitive radio user nodes.
7. All nodes are assumed to be perfectly synchronized so no frequency offset or phase jitter occurs.
8. The nodes location is static, meaning that the location does not change over time.

All of the assumptions above guarantee that the resulting array formed by the sensor nodes is an ideal planar phased array.

III.2.1. **Array Factor and Beampattern**

Let us assume that we have N sensor nodes within the radius R, and let $d_k(\phi, \theta)$ denote the Euclidean distance between the kth node and the destination location (A, ϕ_0, θ_0), where $k \in \{1, 2, \dots, N\}$. The Euclidean distance becomes:

$$d_k(\phi, \theta) = \sqrt{A^2 + r_k^2 - 2r_k A \sin \theta \cos(\phi - \psi_k)} \qquad \text{III-1}$$

The primary concern regarding the beamforming performance is in the far-field region, thus we can assume that $A \gg r_k$. The Euclidean distance becomes:

$$d_k(\phi, \theta) \approx A - r_k \sin \theta \cos(\phi - \psi_k) \qquad \text{III-2}$$

Let us denote Θ_k as the initial phase of the transmit signal carrier of the node k. We set the initial phase as:

$$\Theta_k = -\frac{2\pi}{\lambda} d_k(\phi_0, \theta_0) \qquad \text{III-3}$$

given by the realization of node locations $r = [r_1 r_2 \dots r_N] \epsilon [0, R]$ and $\psi = [\psi_1 \psi_2 \dots \psi_N] \epsilon [-\pi, \pi]$, then the array factor can be defined as:

$$F(\phi, \theta | r, \psi) = \frac{1}{N} \sum_{k=1}^{N} e^{j\Theta_k} e^{j\frac{2\pi}{\lambda} d_k(\phi,\theta)} \qquad \text{III-4}$$

$$= \frac{1}{N} \sum_{k=1}^{N} e^{j\frac{2\pi}{\lambda}[d_k(\phi,\theta) - d_k(\phi_0,\theta_0)]} \qquad \text{III-5}$$

Using the far field approximation of the Euclidean distance, the far-field radiation pattern can be expressed as:

$$F(\phi, \theta | r, \psi) = \frac{1}{N} \sum_{k=1}^{N} e^{j\frac{2\pi}{\lambda} r_k [\sin\theta_0 \cos(\phi_0 - \psi_k) - \sin\theta \cos(\phi - \psi_k)]} \qquad \text{III-6}$$

The magnitude of the above array factor is maximized when the observation angle is equal to the target angle ($\phi = \phi_0$, and $\theta = \theta_0$). In order to achieve this, the initial phase Θ_k should be calculated at each node, which implies that each node must have a precise knowledge of its relative location to the destination. This can be achieved using the closed-loop scenario described in the previous section.

In the open-loop scenario, we choose the initial phase of the kth node as

$$\Theta_k = \frac{2\pi}{\lambda} r_k \sin\theta_0 \cos(\phi_0 - \psi_k) \qquad \text{III-7}$$

The array factor in the far-field region is given by

$$F(\phi, \theta | r, \psi) = e^{j\frac{2\pi}{\lambda} A} \frac{1}{N} \sum_{k=1}^{N} e^{j\frac{2\pi}{\lambda} r_k [\sin\theta_0 \cos(\phi_0 - \psi_k) - \sin\theta \cos(\phi - \psi_k)]} \qquad \text{III-8}$$

This has the same magnitude as the array factor in the closed-loop scenario. In this scenario, precise location of the nodes is required. This can be achieved by coordination of the master node or cluster head.

Finally we can define the far-field beam pattern as the square of the array factor magnitude:

$$P(\phi, \theta | r, \psi) \triangleq |F(\phi, \theta | r, \psi)|^2 \qquad \text{III-9}$$

III.2.2. **Statistical Properties of the Beam Pattern**

Since the locations of the nodes are randomly distributed, the analysis of the beampattern should be done using probabilistic arguments. This is done because the realization of the beampattern is determined by particular realizations of randomly chosen node locations. In [17] Lo has developed a comprehensive theory of random arrays. The main result is that a random array can form a good beampattern with high probability and if the number of antenna elements is N, the directivity of the resulting random arrays approaches N asymptotically.

To give a better overview on this subject, let us observe figure III-4 and assume that the node locations (r_k, ψ_k) are a pair of random variables that follow some probability distribution:

$$f_{r_k}(r) = \frac{2r}{R^2}, \quad 0 < r < R \qquad \text{III-10}$$

$$f_{\psi_k}(\psi) = \frac{1}{2\pi}, \quad -\pi < \psi < \pi, \qquad \text{III-11}$$

Applying the condition that the destination is on the same plane as the nodes ($\theta = \theta_0 = \pi/2$), we have the array factor:

$$F(\phi | r, \psi) = \frac{1}{N} \sum_{k=1}^{N} e^{j \frac{4\pi}{\lambda} r_k \sin\left(\frac{\phi_0 - \phi}{2}\right) \sin\left(\psi_k - \frac{\phi_0 - \phi}{2}\right)} \qquad \text{III-12}$$

$$= \frac{1}{N} \sum_{k=1}^{N} e^{j \frac{4\pi}{\lambda} r_k \sin\left(\frac{\phi_0 - \phi}{2}\right) \tilde{r}_k \sin \tilde{\psi}_k} \qquad \text{III-13}$$

Where $\tilde{r}_k \triangleq r_k/R$ and $\tilde{\psi}_k \triangleq \psi_k - \frac{\phi_0 - \phi}{2}$. Let $z_k \triangleq \tilde{r}_k \sin \tilde{\psi}_k$ be the compound random variable of r_k and ψ_k has the pdf:

$$f_{z_k}(z) = \frac{2}{\pi} \sqrt{1 - z^2}, \qquad -1 \leq z \leq 1 \qquad \text{III-14}$$

Since the above model is asymmetric with respect to the azimuth direction ϕ, a particular choice of ϕ_0 does not change the result in the following. Therefore without loss of generality, we can assume that $\phi_0 = 0$ and the parameter ϕ can be described as the angle difference between the direction and the node ($|\phi| \leq \pi$).

The array factor then can be written as

$$F(\phi|r, \psi) = \frac{1}{N}\sum_{k=1}^{N} e^{-j\,4\pi\tilde{R}\,\sin\left(\frac{\phi}{2}\right)z_k},$$

III-15

Where $\tilde{R} = R/\lambda$ is the radius of the disk normalized by the wavelength.

Finally the far-field beampattern, given the realization of $\bar{z} = [z_1, z_2, .., z_N]$ can be defined as

$$P(\phi|\mathbf{z}) \triangleq E_Z \,|F(\phi|\mathbf{z})|^2 = \frac{1}{N} + \frac{1}{N^2}\sum_{k=1}^{N} e^{-j\alpha(\phi)z_k} \sum_{\substack{l=1 \\ l \neq k}}^{N} e^{j\alpha(\phi)z_l}$$

III-16

Where $\alpha(\phi) = 4\pi\tilde{R}\,\sin\left(\frac{\phi}{2}\right)$

III.2.3. **Average Beampatterns**

The average beampattern of a random array can be defined as

$$P_{av}(\phi) \triangleq E_Z\{P(\phi|\mathbf{z})\}$$

III-17

where E_Z denotes expectation with respect to the random variable Z. Assuming that the random variable z_k are independent and identically distributed (i.i.d.), it can be shown that [1]

$$P_{av}(\phi) \triangleq E_z[P(\phi|\mathbf{Z}_k)] = \frac{1}{N} + 1 - \frac{1}{N}\mu^2(\phi)$$

III-18

where $\mu(\phi) = \left|\frac{2J_1(\alpha(\phi))}{\alpha(\phi)}\right|$

$J_n(x)$ is the nth-order Bessel function of the first kind. The first term $(\frac{1}{N})$ of the average beampattern equation represents the average power level of the sidelobes, which does not depend on the node location. The second term of the equation $(1 - \frac{1}{N}\mu^2(\phi))$, is the contribution to the mainlobe factor.

III.2.4. **Time Percentage of the Average Beampattern**

The calculation of the average beampattern in the previous section does not show the probability for a certain level of power to be received in another direction than the destination. In the realization at one time-slot, the sidelobe power level at a certain direction may exceed the value of the average beampattern in the same direction.
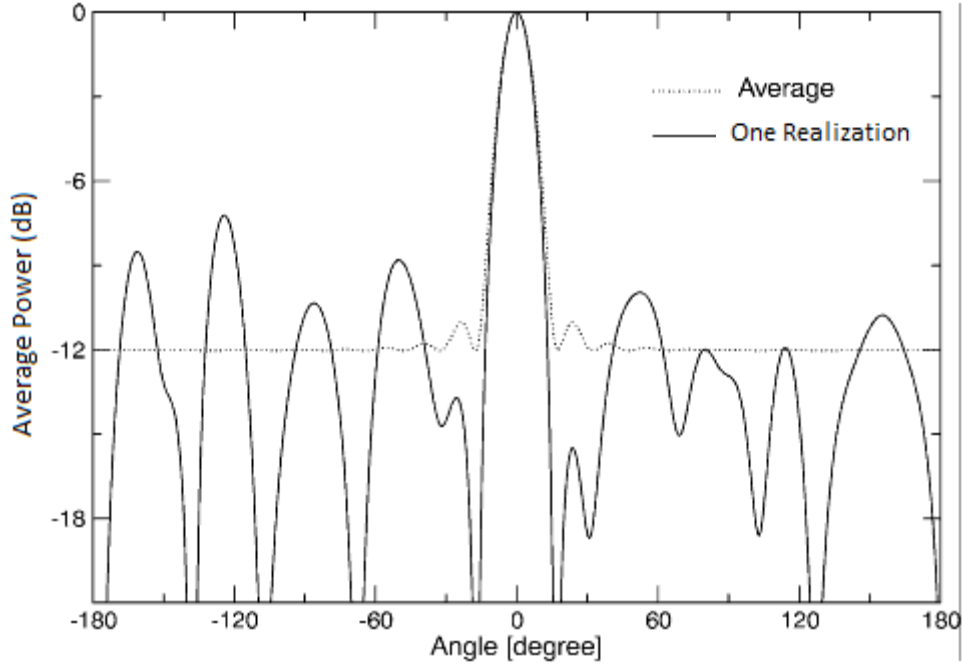
Figure III-5 Realization vs. average [16]

The mainbeam closely matches between the average and the realization, however there is large range where the power exceeds in the sidelobe region. Therefore, in practice or implementation of distributed beamforming, the statistical distribution of beampatterns and sidelobes is of particular interest.

In [18] the author addresses the problem of the probability for a certain amount of energy to be received at a certain direction for the case where a large number of nodes is utilized in t distributed beamforming. CDF (Cumulative Distribution Function) of $P(\phi|\mathbf{Z})$ is presented to show the probability or time percentage as:

$$Prob\ \{P(\phi|\mathbf{Z})|P(\phi|\mathbf{Z}) \leq P_0\}$$

<div align="right">**III-19**</div>

where P_0 is the threshold power, and ϕ is the direction.

When the N is considered large, according the central limit theorem, the array factor ($F(\phi|\mathbf{Z})$) follows the Gaussian distribution. Let us denote:

$$X \triangleq F(\phi|\mathbf{Z})$$

<div align="right">**III-20**</div>

$$Y \triangleq |F(\phi|\mathbf{Z}) - \mu(\phi)|$$

<div align="right">**III-21**</div>

Then $|F(\phi|z_k) - \mu(\phi)|$ follows the Rayleigh distribution

32

$$X \triangleq F(\phi|\mathbf{Z}) \sim \mathbb{N}\left(\mu(\phi), \frac{1 - \mu^2(\phi)}{N}\right) \qquad \text{III-22}$$

$$Y \sim Rayleigh\ (\sigma^2) \qquad \text{III-23}$$

According to properties of a Rayleigh distribution,

$E(y^2) = 2\sigma^2$, and on the other hand $E(y^2) = \frac{1-\mu^2(\phi)}{N}$

We obtain,

$$2\sigma^2 = \frac{1 - \mu^2(\phi)}{N} \qquad \text{III-24}$$

Thus,

$$Prob\{P(\phi|\mathbf{Z})|P(\phi|\mathbf{Z}) > P_0\} = 1 - Prob\{P(\phi|\mathbf{Z})|P(\phi|\mathbf{Z}) \le P_0\} \qquad \text{III-25}$$

$$= 1 - F[\left(|\mu(\phi)| + \sqrt{P_0}\right) - \frac{sgn\left(|\mu(\phi)| - \sqrt{P_0}\right) + 1}{2} F\left(|\mu(\phi)| - \sqrt{P_0}\right)] \qquad \text{III-26}$$

Where $F(x_0) = prob(x|x \le x_0) = 1 - \exp(-x_0^2 N/(1 - \mu^2(\phi)))$ for $x \ge 0$, is the CDF of the Rayleigh distribution of $F(\phi|\mathbf{Z})$, and $sgn(x) = |x|/x$.

For other cases such as when the nodes utilized cannot be considered as small, the CDF calculation is done by Monte Carlo simulation.

III.2.5. **Main Beamwidth Analysis**

In the deterministic antenna, the main beamwidth is defined as the 3-dB beamwidth. The 3-dB beamwidth is the angle of the mainbeam where the power is reduced to half of the total power, or we can denote it as:

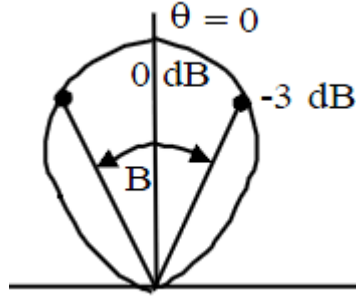$$P_{av}(\phi_{av}^{3dB}) = \frac{1}{2} \qquad \text{III-27}$$

Figure III-6 3-dB beamwidth

In this thesis work, we will do the analysis of the main beamwidth based on this theory. The importance of the beamwidth is that it determines the coverage of the communication beam, since the information is contained in the mainbeam region. The beamwidth required varies from each different application, if the mainbeam width is too large, it can cause severe interference to other communication links in the direction around the mainbeam. However, in a case where the far-field destination node has mobility, narrow mainbeam may not be desirable. This is why the beamwidth has to be designed carefully.

In the case of distributed beamforming, the derivation of 3-dB beamwidth calculation has been done in [16], in the limit as $N \rightarrow \infty$,

$$\phi_{av}^{3dB} = 2 \, arcsin\left(\frac{0.1286}{R}\right) \qquad \textbf{III-28}$$

From the equation above, we can see that when the number of nodes utilized is very large, the beamwidth is mainly determined by the inverse of the disk radius of the cluster normalized by λ.

CHAPTER IV

DISTRIBUTED BEAMFORMING FOR COGNITIVE RADIO

IV.1. **System Model**

After we study the principal of distributed beamforming and the advantages of its implementation, in this section we present the implementation of distributed beamforming in cognitive radio network. We study a cognitive radio network with cognitive users communicating to each other in the presence of licensed users.
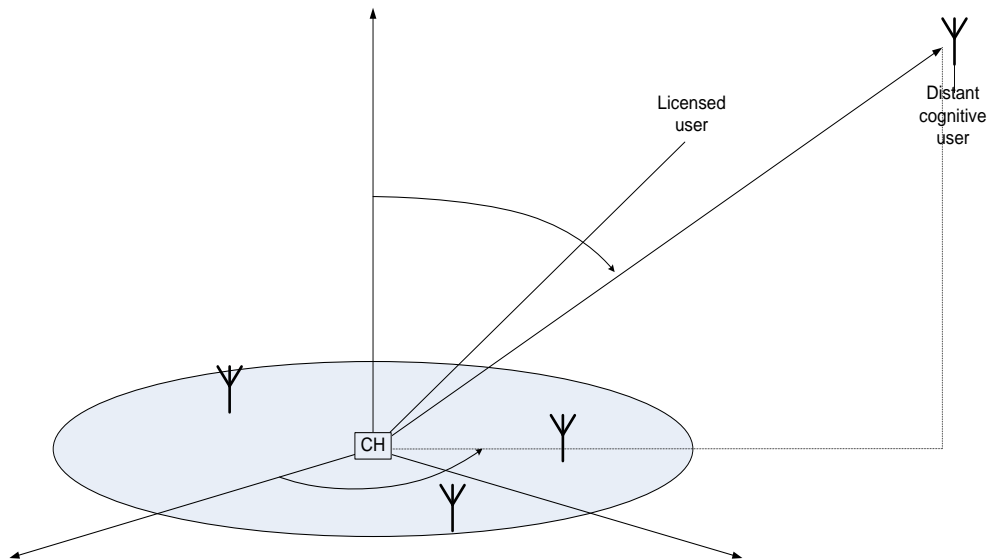
Figure IV-1 Distributed beamforming in cognitive radio

To achieve the efficiency in prolonging the lifetime of the nodes, the network is divided into clusters. Each cluster is in a disk of radius $\tilde{R}$ and has a cluster head (CH). The cluster head which is located in the center of the circular plane is a cognitive node which holds the information of the location of the nodes and a priori knowledge of the direction of the LU and destination node. This can be achieved by message exchanges before the cooperative beamforming.

There are several methods to choose the cluster head, some of the methods are [21-25]:

- LEACH (Low Energy Adaptive Clustering Hierarchy): since the cluster head node collects data from the other nodes, the energy consumption will be large consequently. Thus, the cluster head is changed periodically in order to disperse the energy consumption over the entire cluster.
- LEACH-C (Centralized): In this method, the cluster head selection is selected based on the recent condition of each node by the base station. All of the distributed nodes send a message which contains the information about their location and energy level to the base station. The base station then sends a broadcast message to the entire distributed nodes regarding the cluster head selection.
- HEED (Hybrid, Energy-Efficient Distributed): the selection of the cluster head is based on the residual energy of each node. The node which has the most residual energy is selected as the cluster head. When there are nodes with the same amount of residual energy, then their transmission costs are brought into consideration.
- BCDCP (Base station Controlled Dynamic Clustering Protocol): this method uses the same method as the LEACH-C in some parts. The base station elects a candidate set of cluster heads, cluster splitting algorithm which divides the network continuously is used to fit the number of cluster heads.

In this thesis work we will not consider the process of cluster head selection, it is assumed to be already selected for each of the clusters. All of the cognitive nodes are distributed uniformly within a circle, and they are contributing an amount of power to the distributed beamforming in order to establish a communication link to the destination. We assume the destination is on the same plane as the users ($\theta = \theta_0 = \pi/2$). Other assumptions used in this system model are already described in the previous chapter (chapter 3).

The main consideration in implementing distributed beamforming in cognitive radio is to avoid interference to the licensed user. In order to achieve this, the beampattern generated by the distributed beamformer must have a narrow main beam in order to avoid interference in the direction around the destination node. However, too narrow main beam is also not good, since sometimes a location error exists. We assume the destination location is acquired by using GPS (global positioning system) which has some degrees of error (non-military version).

Noise is also considered to contribute to the location error. The main beam width has to cover the area around the location error. Another requirement of the beampattern is the low sidelobe power level, especially in the direction of the licensed user. This is required due to the interference avoidance to directions other than the destination.

In this system, CR users and licensed users co-exist with each other. We assume the CR nodes are small battery powered radio devices equipped with a single isotropic antenna. The LU requires the CR system to obey several requirements in order for both the LU and CR users to be functional. In order to understand the effect of the LU presence, let us denote the LU requirements in the system as:

$$LU\ [\phi, P_0, t_0] \qquad \text{IV-1}$$

Where ϕ denotes the direction of the LU, P_0 (in dB) is the maximum interference power at the direction of LU. Ideally, we want the power transmitted by the CR users to the LU to be as small as possible. We can also call this "power threshold of the LU". t_0 is the probability of power reaching a certain value (P_0) in the direction of the LU. This probability can also be explained as time percentage of the power radiated by the CR users to the LU users is lower than the P_0 (power threshold).

From the average beampattern equation:

$$P(\phi, \theta | \mathbf{z}) \triangleq |F(\phi, \theta | \mathbf{z})|^2 = \frac{1}{N} + \frac{1}{N^2} \sum_{k=1}^{N} e^{-j\alpha(\phi)z_k} \sum_{\substack{l=1 \\ l \neq k}}^{N} e^{j\alpha(\phi)z_l} \qquad \text{IV-2}$$

It already concluded that the first factor ($\frac{1}{N}$) contributes to the average power level of the sidelobes. We can say that the larger the number of nodes utilized, the lower the sidelobe level is regardless of the node location with the limit as $N \to \infty$.

Based on those previous results, we can conclude that we need a large number of CR users distributed in a large area to generate a beampattern which has a narrow main beam and low sidelobe level to be implemented in the CR networks. However, utilizing a large number of nodes to establish communication beam also affects the energy consumption. When large numbers of nodes are utilized to generate a beam, the energy consumption will also be large. On the other hand, the number of nodes used in DB affects the sidelobe level of the beampattern. Utilizing a small number of nodes will give a high sidelobe power level. This

condition will cause interference to other communication systems. This is why, the optimal node number is important when applied to a cognitive radio network in order to keep the energy consumption efficient and assuring the QoS (quality of service) of nearby communication links (e.g. licensed users). This is aligning with the green communication concept which supports the conservation of power when establishing communication links, thus prolonging the lifetime of the distributed devices.

In this thesis work, we will conduct experiments in order to optimize the nodes utilized by the system to do the beamformer based on the LU requirements. The node number selection method will be presented in section IV.2. We also present several node selection algorithms to determine which nodes should be used in the distributed beamforming in the following chapter. The node selection algorithms are:

1. Euclidean based node selection: this node selection method is based on the Euclidean distance of each node. The area over which the nodes are distributed is divided into N areas, and we will assign one node from each of the area to the distributed beamforming. The motivation of this method is to ensure that each of the nodes selected is located as sparsely as possible to each other's.

2. Sector based node selection: in this method, we select the nodes from an area which we decide beforehand. We will present the result of the beampattern generated for different sizes of sectors. Opposite sector selection, where the nodes selected are from two different sectors with opposite direction. It is also possible to do multi-beam generating based on this node selection method.

3. Ring and circle range node selection [18]: this node selection method originally comes from the idea of multi beam generation where the circular plane is divided into two smaller area, an inner circlular area and an outer ring area.

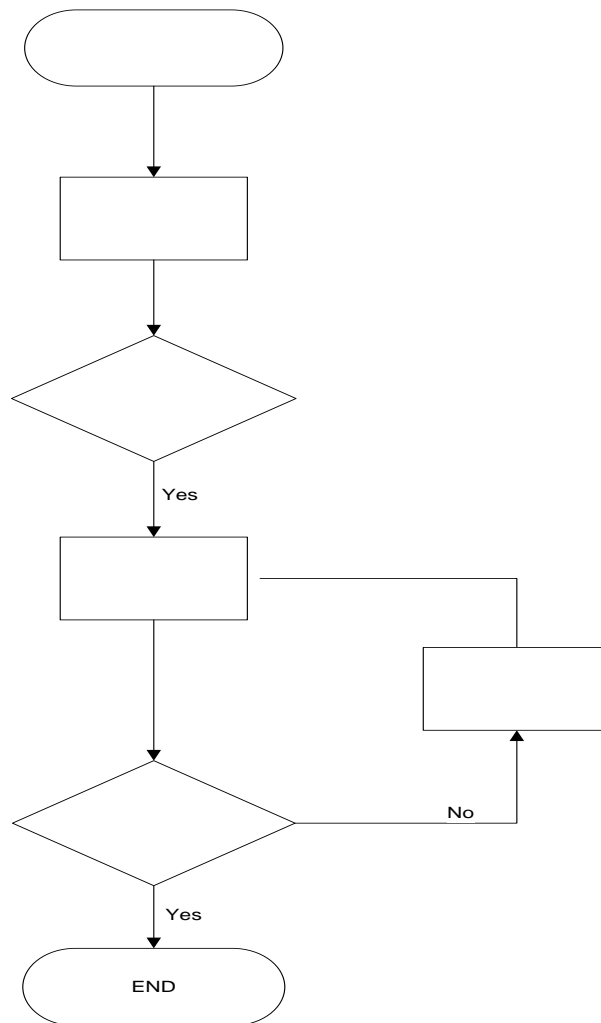## IV.2. **Optimal Node Number Selection**

Figure IV-2 Optimal node number selection

The flow chart in figure IV-2 describes the optimal node number selection based on the LU requirement. The method itself consists of two steps; first we start by choosing a proper number of nodes which can be considered as small. We then examine the sidelobe power level ($P_0(N)$) at the direction of LU. This $P_0(N)$ value cannot exceed a certain value which is determined by the licensed user. When the number of nodes is large the sidelobe level of the beampattern can be described as [16]:

$$\lim_{N \to \infty} \frac{1}{N} \leq P_0 \,, \ \therefore N \geq \frac{1}{P_0} \qquad \textbf{IV-3}$$

By the end of the first step, we will obtain a number of utilized nodes described as N. This value of "N" is the least number of nodes to be utilized in the second step of the algorithm.

The second step of this method is to examine whether the obtained value of N satisfies the t_0 requirement of the LU. This step is done due to the statistical property of the distributed beamforming itself as described in chapter 3. We calculate the CDF of the beampattern on the direction of LU using the N obtained from the first step. The CDF analysis of the beampattern shows us the probability of power level of the average beampattern. We introduce the parameter t_0 as one of the constraints which denotes the minimum probability of the sidelobe that not exceeds a certain power level. In the derivation of the CDF formula presented is the previous chapter (3), we can see that if the number of nodes utilized is considered as small the distribution of $F(\phi|z_k)$ does not follows the Gaussian distribution any longer, thus the absolute value of $F(\phi|z_k) - \mu(\phi)$ also does not follow the Rayleigh distribution.

Therefore the formula III-26 in chapter 3 does not satisfy any longer and the CDF calculation is done by Monte Carlo simulation.

By the end of these steps, we will obtain a number of nodes which is optimal regarding the power consumption of the nodes and also satisfies the LU's requirements.

IV.3. Node selection methods

Several node selection methods have been proposed in the literature for collaborative beamforming. One of the applications of the collaborative beamforming is for wireless sensor networks, in [19] the author randomly selects the utilized nodes. The selection is based on the P_{thr}, which was the threshold power of the receiver. Sets of utilized nodes are selected randomly, and then a beampattern is generated using the node set. If the threshold requirement is not fulfilled, the previous set is expelled from the selection process. The selection process repeats itself until the threshold requirement of the receiver is fulfilled.

One of the proposed methods is the phase partition method for wireless sensor networks [20]. In this method, the author tried to find a suboptimal set of sensor whose radiation is added coherently but not necessary optimal along the receiver direction.

There are two steps in the method, such as:

1. Phase term (x_i) is wrapped in the range of $[0,2\pi]$.
2. The span of the phase is separated into N partitions, and then the sensors are grouped together based on their phase.

As long as $N > 2$, each sensor in the group will contribute the same sign of the field; so no destructive interference occurs.

Another node selection algorithm is for wireless ad hoc networks [21]. The method is based on two criteria. The first criterion is to maximize the power in the intended direction, the second one is to suppress or minimize the power to the un-intended direction.

1. Maximum mainlobe power criterion: it is used to maximize the desired direction power
2. Minimum average sidelobe power criterion: it is used to minimize the average power to the un-intended directions.

In this thesis work, after we obtain the number of nodes which should be utilized to perform the distributed beamforming, we will choose the nodes from the total distributed nodes. We will present several node selection methods, including recent work on the node selection and then we will compare the performance of all the methods. The comparison is based on the mainlobe and sidelobe analysis with the presence of LU.

IV.3.2. **Euclidean distance based node selection**

The basic idea of the algorithm is to minimize the phase differences between the nodes which contribute to the total power of the beampattern. Let us consider two electromagnetic waves with different phases added together [20]

$$E_1 = \exp\big(j(2\pi r_1 + \psi_1)\big) = \exp(jX_1) \qquad \textbf{IV-4}$$

$$E_2 = \exp\big(j(2\pi r_2 + \psi_2)\big) = \exp(jX_2) \qquad \textbf{IV-5}$$

The total power of the two waves is:

$$P = |E_1 + E_2|^2 = |1 + \exp(j(\Delta X))|^2 \qquad \textbf{IV-6}$$

Where $\Delta X = X_1 - X_2$ is the phase difference of the waves.

From the equation we can conclude that the smaller the phase difference, the higher the total power is since the waves are constructive to each other. However, this only affects the mainlobe of the beampattern because the phase of each wave is the relative position of the corresponding nodes from the destination. From the recent work in the field of distributed beamforming it is already concluded that in order to get low sidelobe level, the nodes have to be located as sparsely as possible [16].

From the facts described above, we try to do node selection based on the Euclidean distance of the nodes.
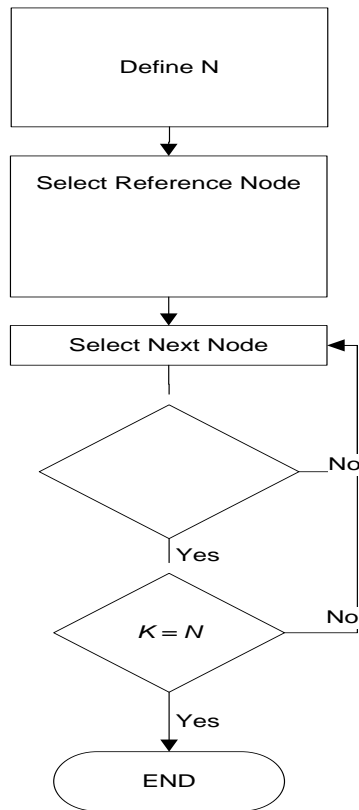
Figure IV-3 Euclidean based node selection method

We can describe the method into several steps:

1. Define the number of nodes in a set from the total distributed nodes in the area using the method proposed before.

2. Select the reference node from the distributed nodes. The selection of the reference node consists of two constraints. We select the reference node based on the smallest phase difference with the destination node. The second one is based on the location of the reference node in the area; we choose the reference node which is closest to the destination node. If (r_k, ψ_k) is the location of a node in an area, the reference node has to satisfy:

$$\begin{cases} r_k = max \\ \psi_k - \phi_0 = min \end{cases}$$

3. In the selection of the next nodes, we want to select a set of nodes which are located as sparsely as possible from each other. In order to achieve this, we divide the area into

$360/N$ sectors, and we select one node from each sector. We use the Euclidean distance of each nodes to satisfy this,

$$d = \sqrt{r_1{}^2 + r_2{}^2 - 2r_1 r_2 \cos(\psi_1 - \psi_2)} \qquad \text{IV-7}$$

where d is the Euclidean distance between two arbitrary nodes. We select the next node which has $d \geq d_0$. d_0 is the minimum distance between two utilized nodes. We choose the value of d_0 according to the number of sectors and the size of the sectors.

Another constraint is that the phase difference of the present node and the next node also has to be larger than the angle of each sector. This way, to the best of the author's knowledge, the location of each node can be guaranteed to be located as sparsely as possible.

$$\begin{cases} d \geq d_0 \\ |\psi_k - \psi_{k-1}| \geq \dfrac{360}{N} \end{cases}$$

4. Repeat step 3 until a set of N nodes is selected.
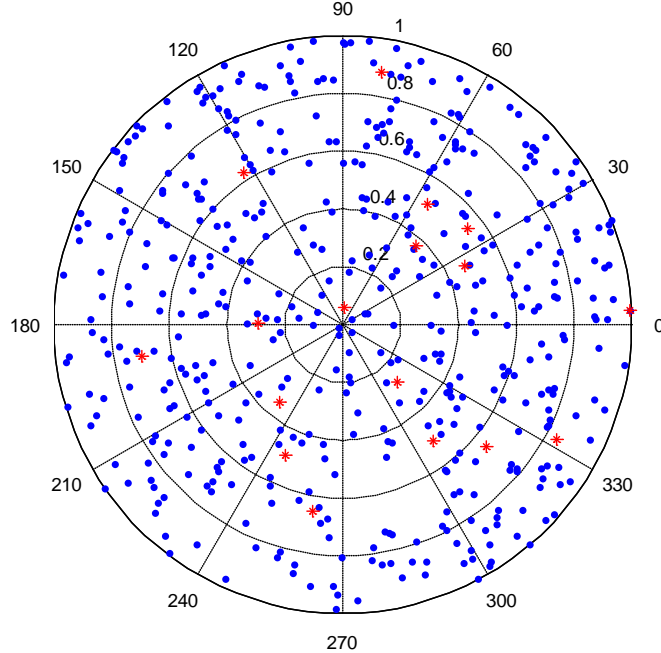
Figure IV-4 Selected node using the Euclidean based method

The red node which is closest to the $0°$ direction is the reference node, and the rest is selected using the method. For all the results presented, the destination is on the angle of $0°$.

IV.3.3. **Sector Based Node Selection**

When the nodes utilized to form a beampattern are close to each other, the performance of the mainbeam will be improved according to the theory [20]. We present a node selection method where the nodes selected belong to an area of sector with certain area in the circular plane. Recent works show that multi beam generation is also of interest in the field of distributed beamforming. The sector position itself is defined by the direction of the destination. In this way, we can divide the distributed nodes in the area to form multiple beams to multiple directions. However, in order to achieve sparse location between nodes, we also apply the Euclidean based selection with certain value of d_0.
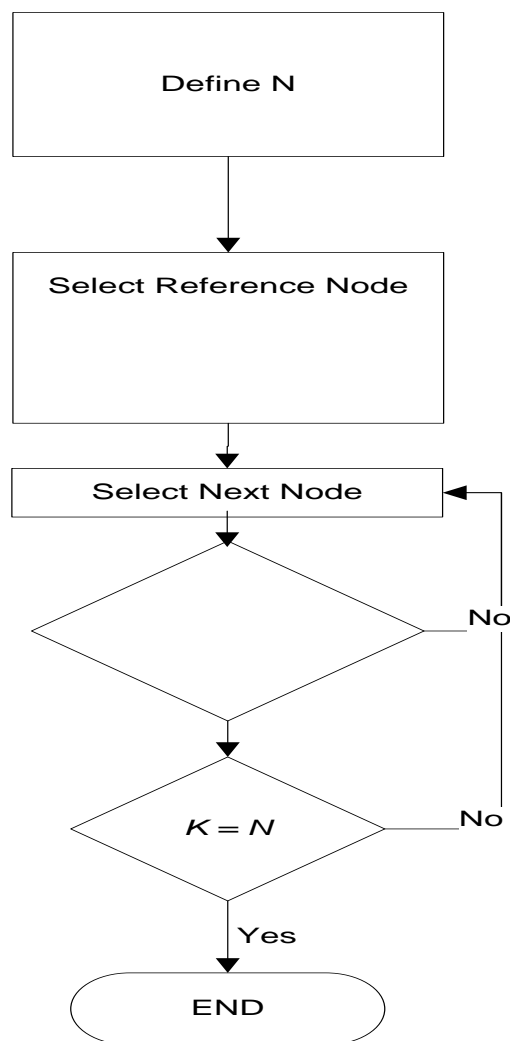

Figure IV-5 Sector based node selection

This method consists of the same steps as the Euclidean based method, the only difference is that the nodes selected have to be in the area which we define before.

We will present 3 specifications on this method:

1. Small sector: in this specification, we will choose the utilized nodes from the area in the circle which have $60°$ width.
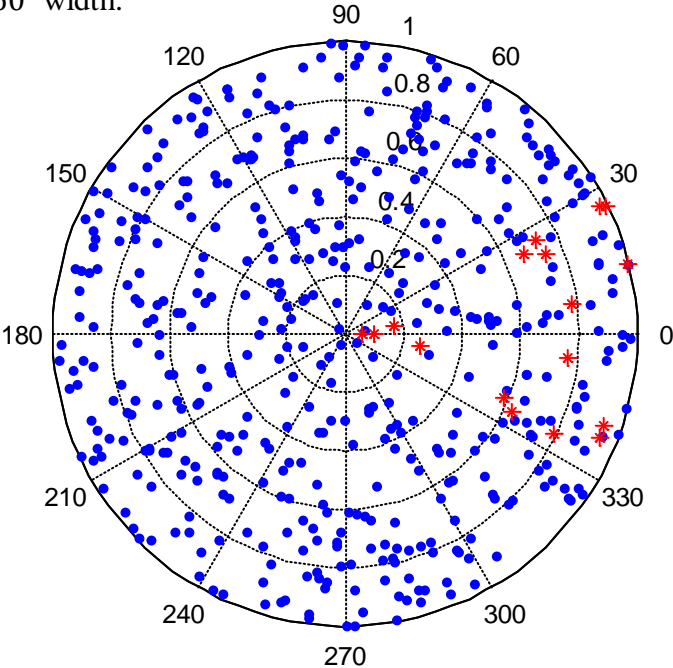

Figure IV-6 Sectorized based node selection (small sector)

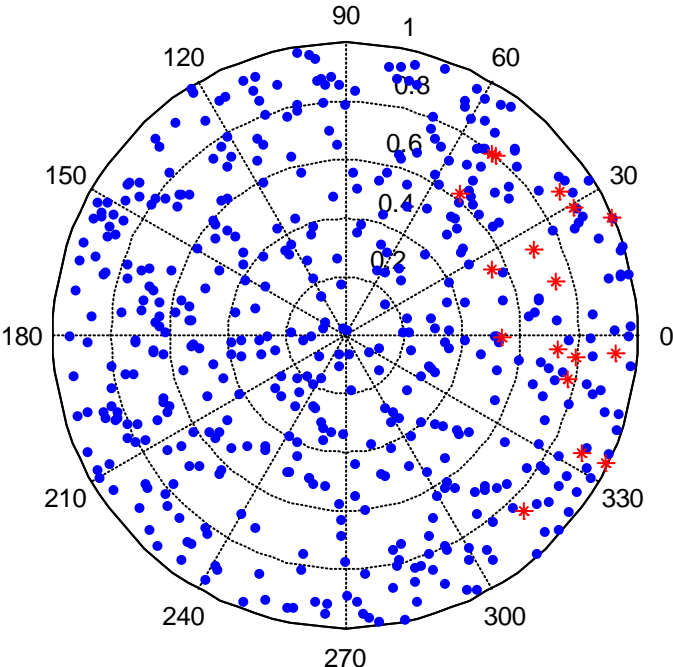2. Large sector: we choose the utilized nodes from $120°$ width sector.

Figure IV-7 Sectorized based node selection (small sector)

3. Opposite sector: we choose the utilized nodes from two sectors which are opposite in location
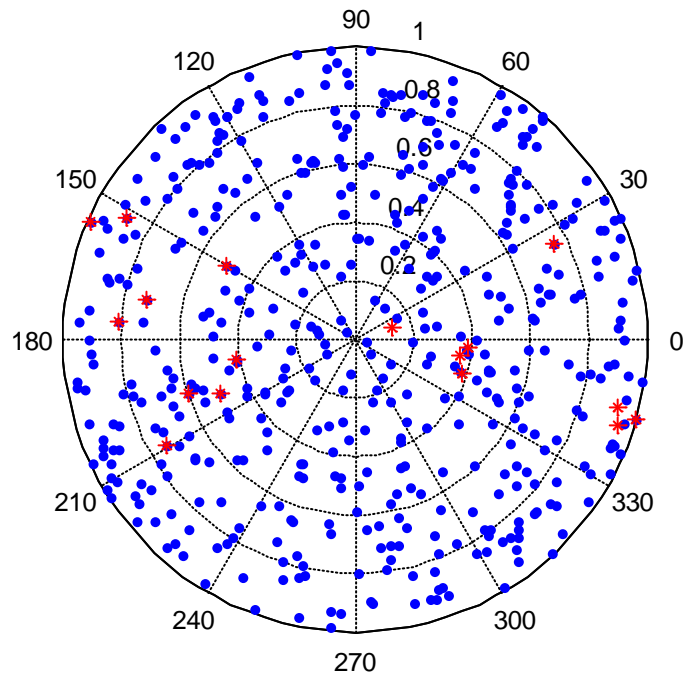

Figure IV-8 Sectorized based node selection (opposite sector)

IV.3.4. **Ring and Circle Range**

Multi beam generating method is presented in [18] by dividing the area of distributed nodes into two ranges namely ring and circle range. We will examine the effect if we distribute the utilized node in these areas.
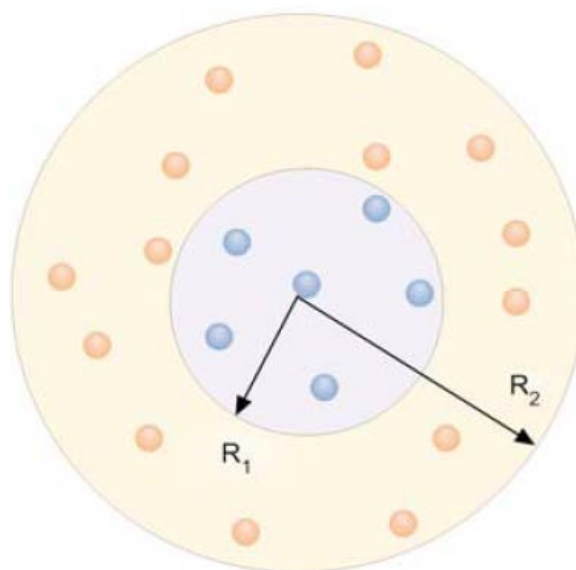

Figure IV-9 Ring and circle range

We will apply the same optimal node selection as in method 1, but with a different constraint. We select one node from each sector, but the value of r_k has to be smaller than $\tilde{R}_1$ for the circle range, and $\tilde{R}_1 \leq r_k \leq \tilde{R}_2$ for the ring range. $\tilde{R}_1$ is the radius of inner circle range area, and $\tilde{R}_2$ is the radius of the whole circle area.
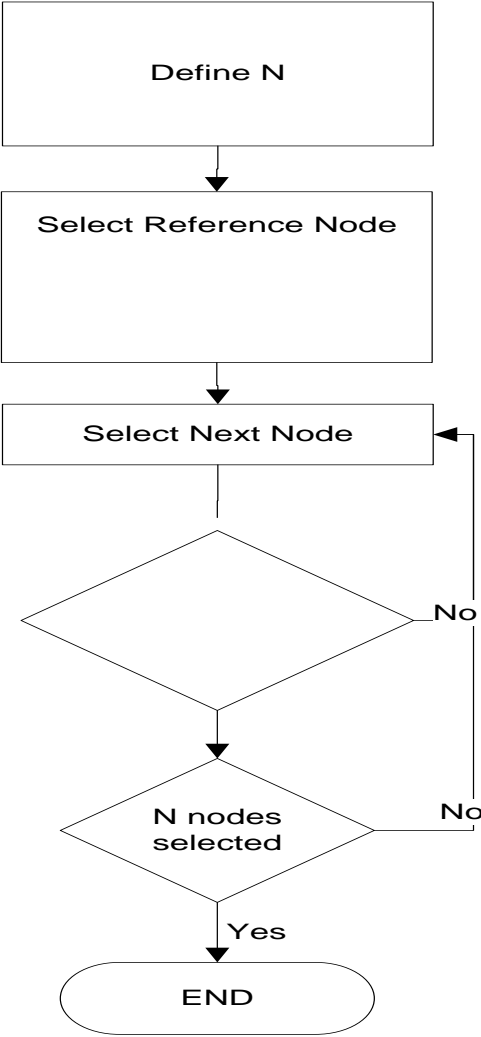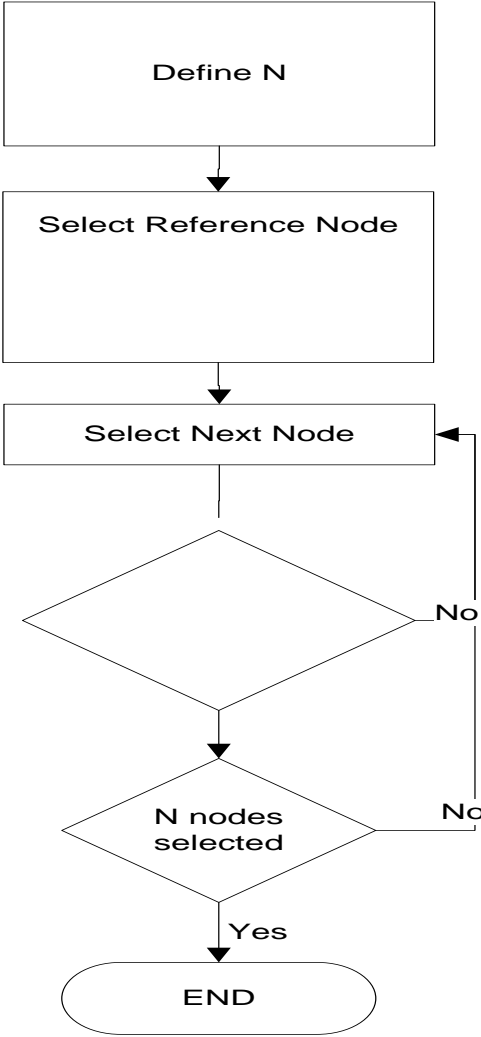

Figure IV-10 Circle range method   **Figure IV-11 Ring range method**

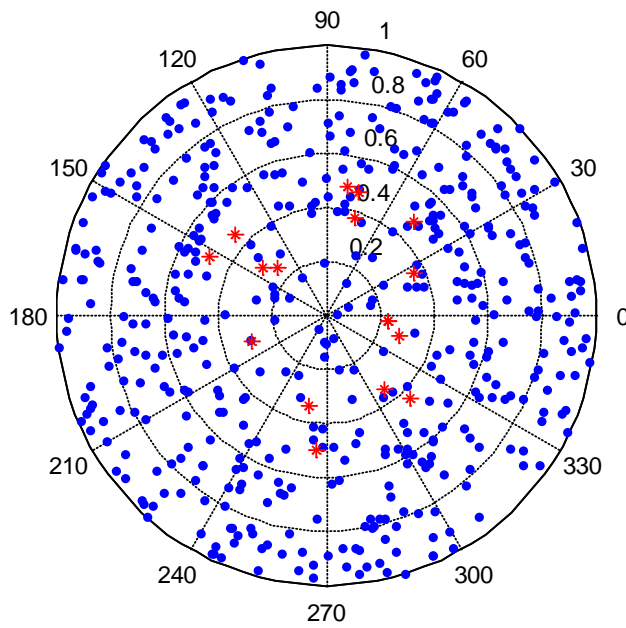In this thesis work, we choose the $\tilde{R}_1$ as $0.5\tilde{R}$, and $\tilde{R}_2 = \tilde{R}$
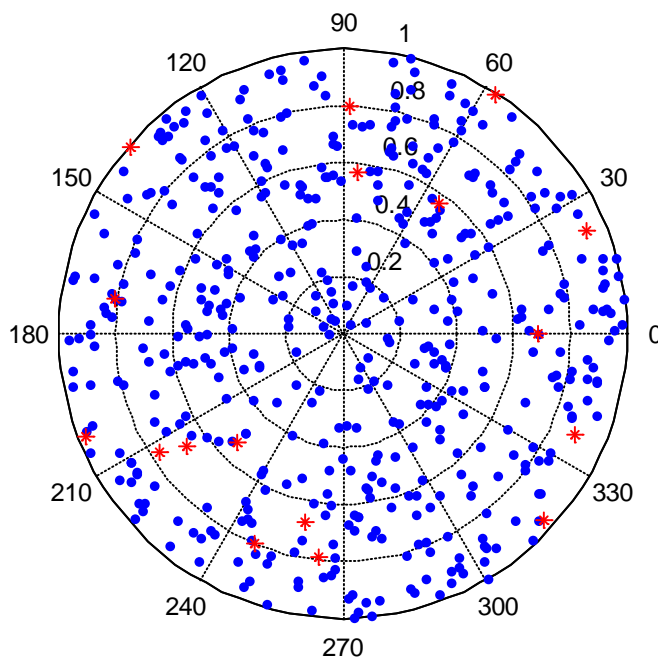

Figure IV-12 Circle range node selection

Figure IV-13 Ring range node selection

CHAPTER V

RESULTS AND DISCUSSION

V.1. **Simulation scenario**

In this section, we will show the results of the proposed algorithms. The scenario we use in this thesis is a distributed cognitive radio system with nodes in a circular plane, with the radius normalized by λ: $\tilde{R} = 4$. We perform Monte Carlo simulation 10.000 times in order to show the average result of the beampattern. The direction of the destination node is set to 0°, and the results will be presented in Cartesian coordinates. The LU requirements which will be used in the entire simulation are

$$LU\ [30^{\circ}, -10\ dB, 80\%]$$

V-1

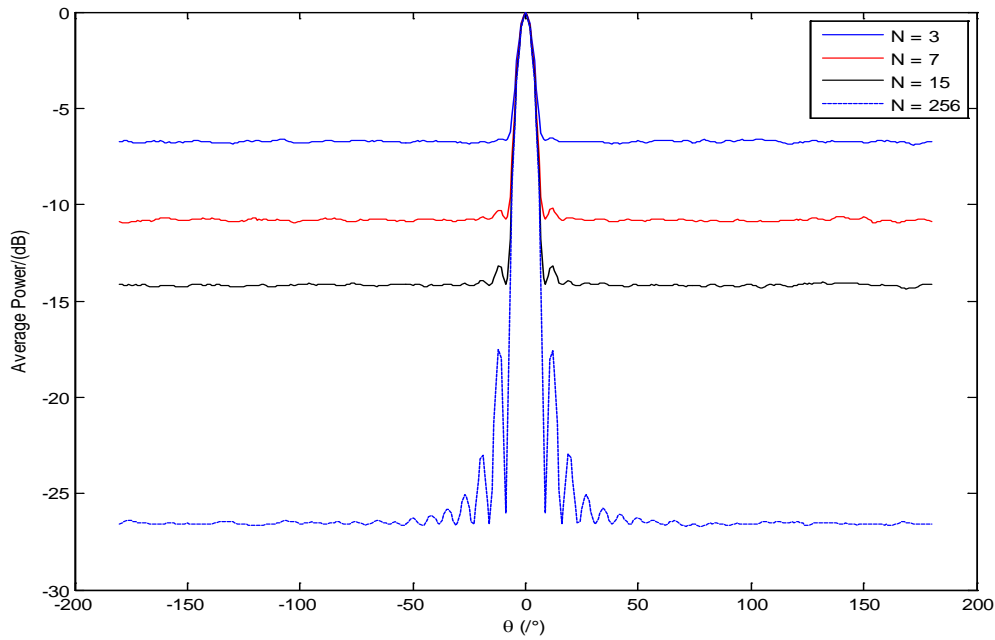### V.2. **Optimal node number selection results**

Figure V-1 Average beampattern with $\tilde{R} = 4$ and different N

We conduct the simulation based on the method which has been described in section IV.2. The first step is to examine that the power radiated by the cognitive radio nodes towards the destination angle does not exceed the threshold power (-10 dB). As we can see from figure V-1, utilizing 7 nodes in the distributed beamforming will give a beampattern where the sidelobe

in the direction of LU ($P_0(N)$) is lower than -10 dB. Since we use the same node selection method, we can see that when we increase the number of utilized nodes, the sidelobe power level will decrease but the mainbeam width stays the same. This result aligns with the result of previous works in the field [16], thus can be validated.

The next step of the method is to examine the time percentage of the beampattern at certain power level or the CDF. We use Monte Carlo simulation to calculate the CDF since the number of N is relatively small. The result of the CDF simulation is presented in figure V-2:
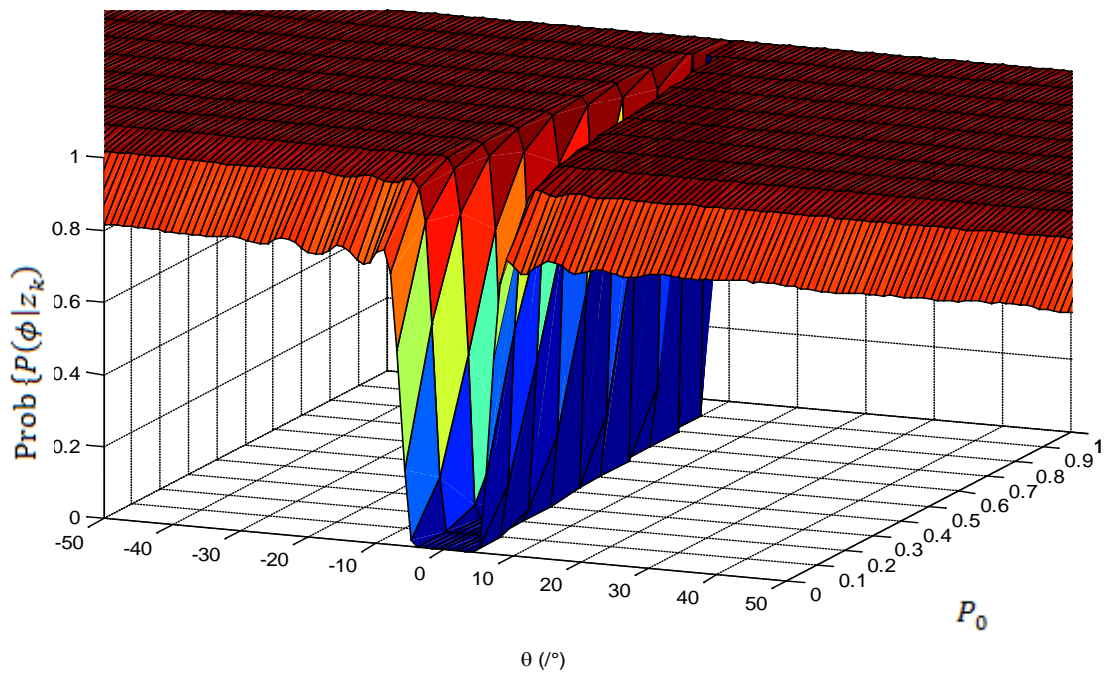
Figure V-2 CDF of the average beampattern at every angle

The "x" axis shows the direction angle, the "y" axis shows the time percentage of the beampattern does not exceed the power threshold, and the "z" axis shows the power threshold level which we want to examine. If we see the figure from the "z" axis side, we can examine the CDF at all threshold power levels. We can see that in the direction of the mainbeam ($0^{°}$), the probability that the power is lower than the threshold power is 0 %. This result means that the mainbeam of the beampattern generated is guaranteed to have the maximum power compared to any other direction. When we examine the figure from the "x" axis side, we can see that the slope size in the direction of the main beam decreases as the threshold power increases. Consequently, we can say that when the P_0 requirement of the LU is relaxed (P_0 increases), more area can be occupied by the LU in CR network.

Based on the LU requirement, we want to examine the time percentage of the power radiated by the cognitive users towards the licensed user. We will display the result of Prob $\{P(\phi|z_k) < 0.1\}$ at every angle.
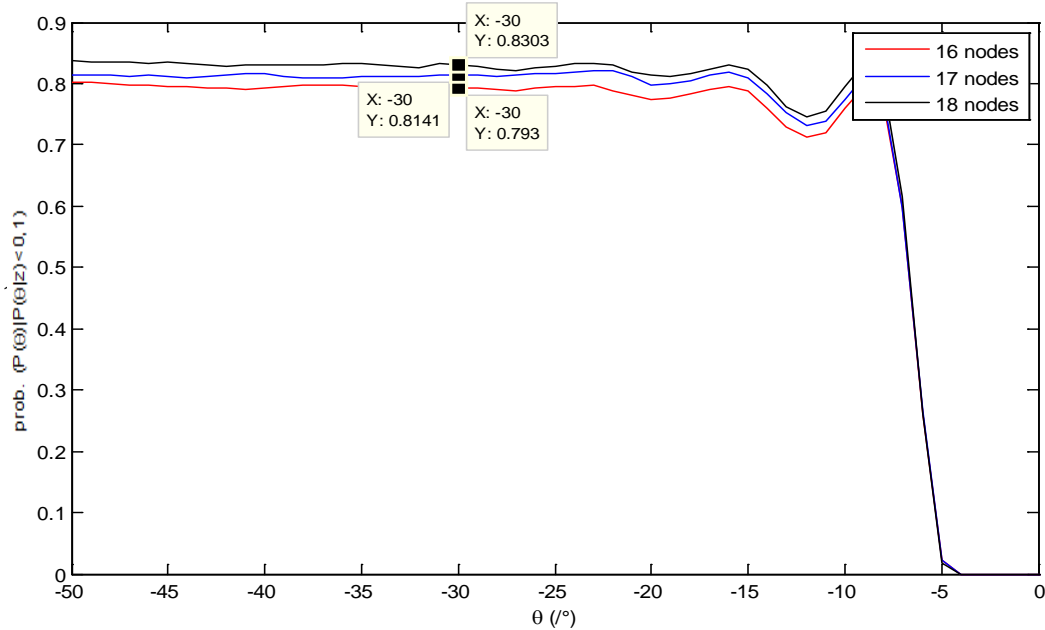

Figure V-3 Time percentage of $\{P(\phi|z_k) < 0.1\}$ (N = 17) at every angle

Based on the first step, we obtain that 7 nodes is the minimum number of nodes to be used in the distributed beamforming. The next step is to apply the N value obtained to the calculation of $t_0(N)$. After the iteration, we conclude that 17 nodes utilized by the distributed beamforming satisfy the LU requirements as shown in Figure V-3. Utilizing 17 nodes gives us 81.4 % of the time; the power radiated in the direction of LU is lower than -10 dB.

From this simulation result of the node selection algorithm, based on the LU requirements of

$$LU\ [30^\circ, -10\ dB, 80\%]$$

<div align="right">**V-2**</div>

We can apply distributed beamforming in a cognitive radio network to form a communication beam towards the destination by using 17 nodes of the total distributed nodes within an area without causing interference to the licensed user.

V.3. **Node selection algorithm results**

In this section, we will present the beampattern of the node selection algorithm. The nodes used in this simulation are 17 nodes.
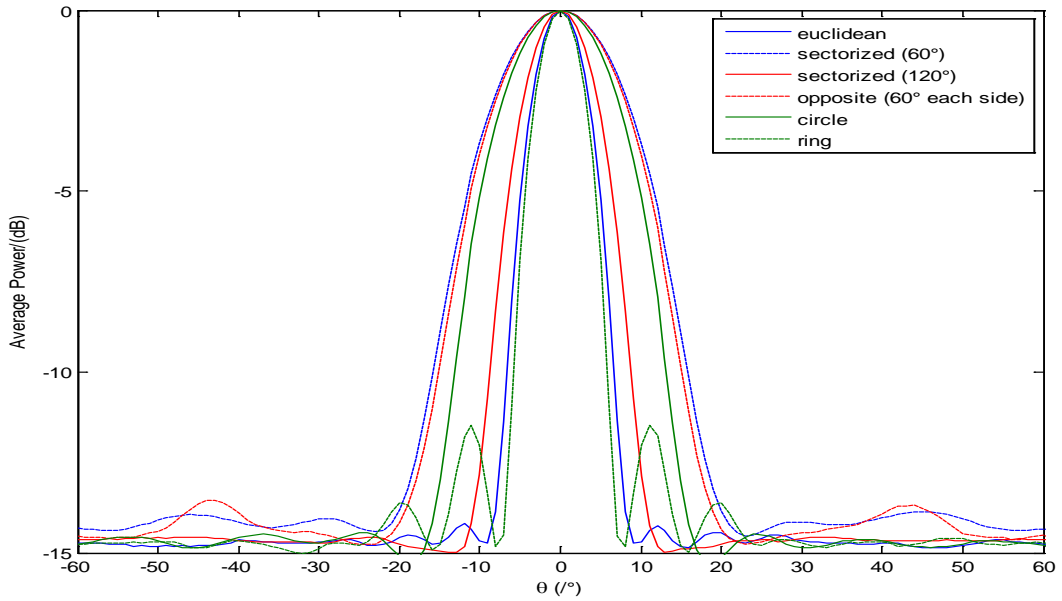
Figure V-4 Average beampattern with $\widetilde{R}$ = 4 and N = 17

From the result we can see that in the direction of the licensed user (30°), the sidelobe power level does not exceed -10 dB. We can conclude that all of the node selection methods presented is valid to be applied based on this requirement.

The next requirement is the time percentage of the beampattern at the direction of the licensed user. The result is presented in the figure V-5:
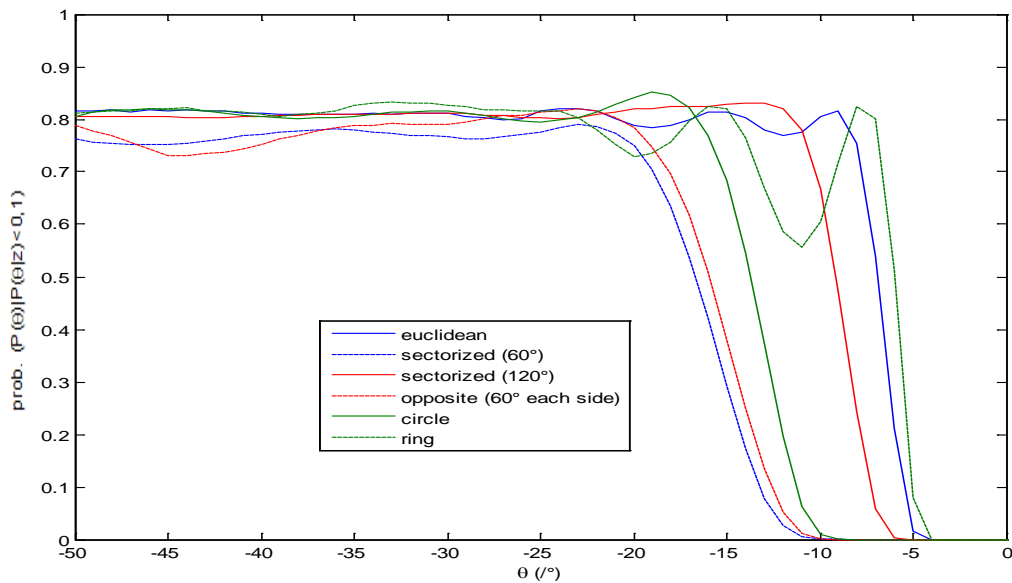

Figure V-5 Time percentage of $\{P(\phi|z_k) < 0.1\}$ (N = 17) at every angle

From the result we can see that aside from the small sector and opposite sector method, all the other methods give 81.6 % or more chance that the power radiated by the CR users towards the licensed user is lower than -10 dB. Furthermore, if we add the main beam width and the sidelobe power level behavior, we can conclude that the Euclidean based and the large sector node selection give the best result among the node selection methods presented. The Euclidean based method gives a narrower main beamwidth, which means more room is available for co-existence with licensed users. The "ring range" method gives narrower main beam width than the Euclidean method. However, the first sidelobe of the method gives a large power level and thus should be avoided because it tends to interfere with other communication systems in the direction around the destination. The large sector based method gives more stable sidelobe power level at any other direction, which means that the interference in the other direction aside from the destination can be more "controllable".

V.4.   **Node selection methods comparison**

To further investigate the comparison of the node selection method, we will apply the node selection method into several different scenarios. First, let us consider a cognitive radio network where a licensed user is co-existed but with different requirements. When the LU requirements are stricter (lower P_0, higher t_0), the number of nodes utilized will have to cope with the condition. Based on this probable scenario, we can say that beampattern result of different value of N is of a particular interest. We already presented the result when the nodes utilized in considered as "small", now let us consider if the nodes utilized is considered as "medium" and "large". For the medium scenario we choose 50 nodes out of the total distributed nodes to be utilized. We select the number 100 for the large scenario. The results of these simulations are presented in the figure below:
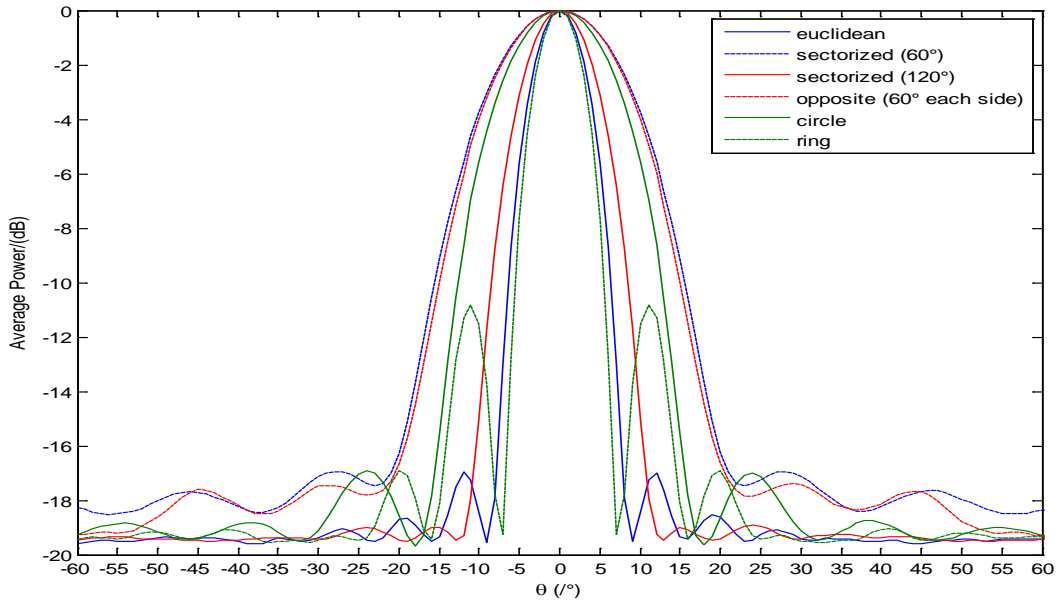
Figure V-6 Average beampattern with $\tilde{R}$ = 4 and N = 50
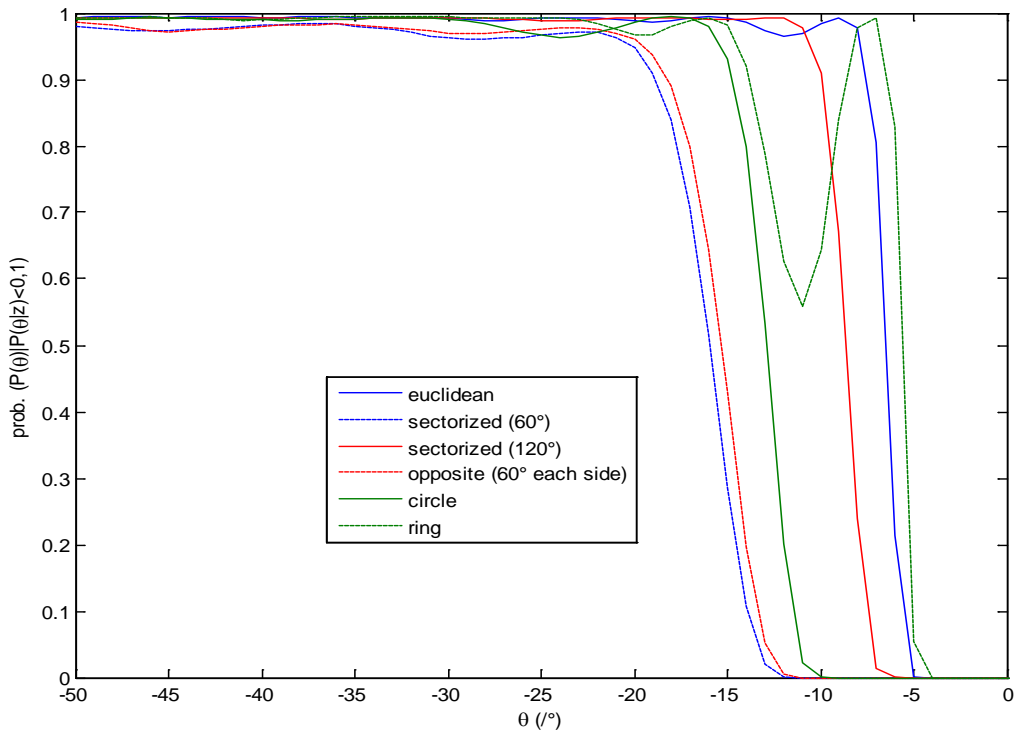

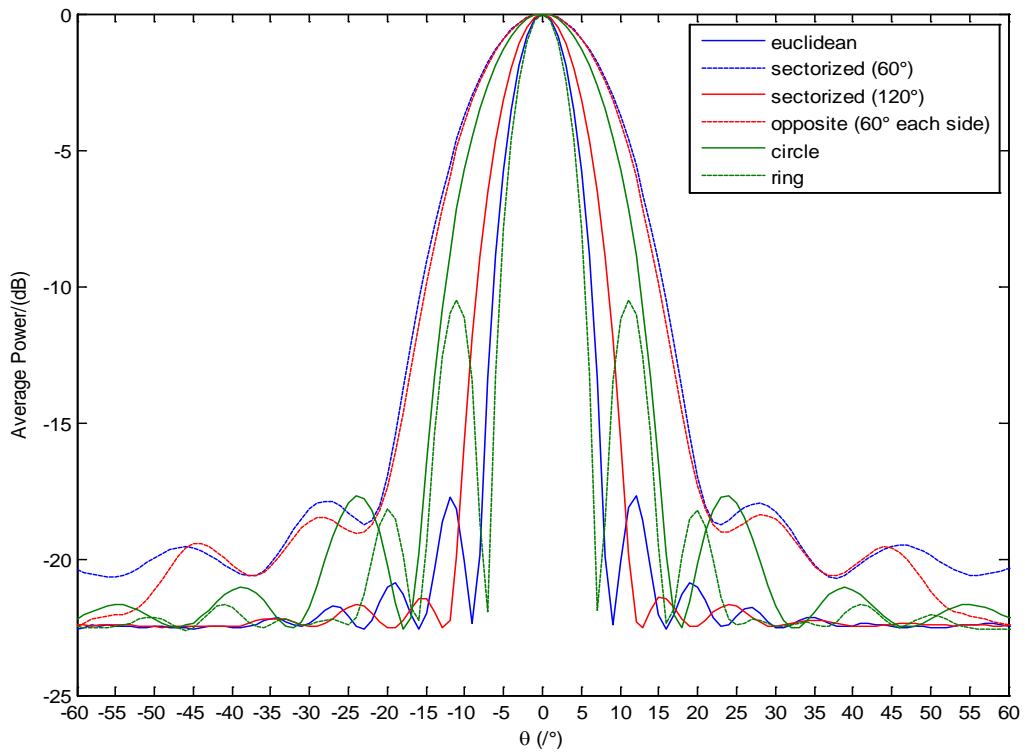**Figure V-7 Time percentage of $\{P(\phi|z_k) < 0.1\}$ (N = 50) at every angle**

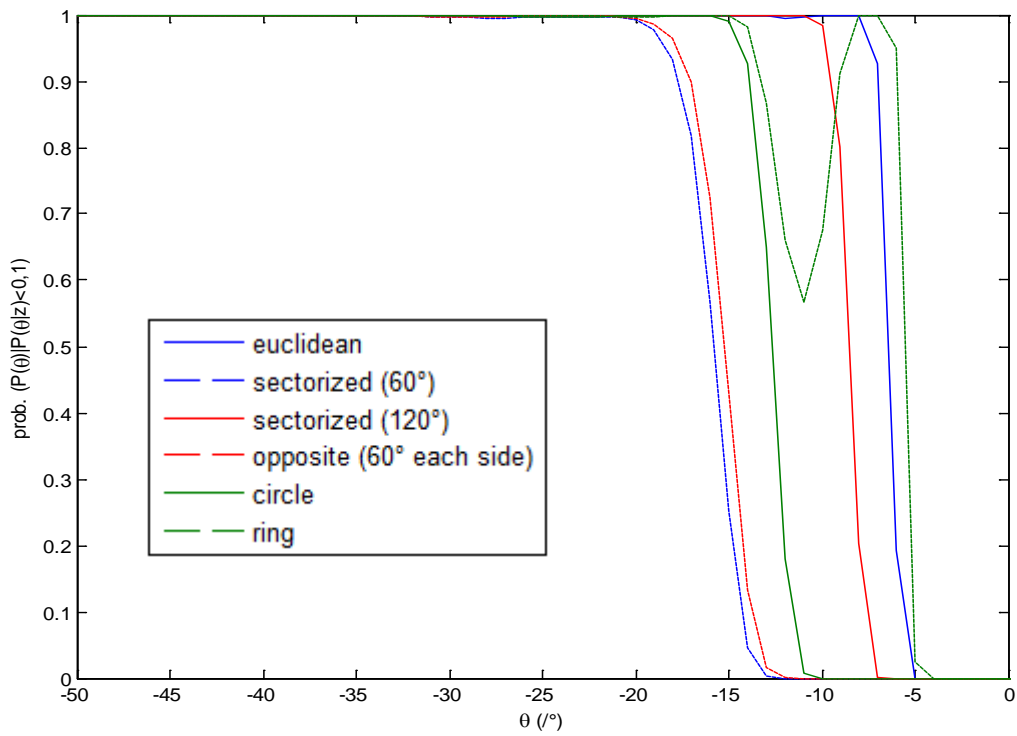**Figure V-8 Average beampattern with $\widetilde{R} = 4$ and N = 100**

Figure V-9 Time percentage of $\{P(\phi|z_k) < 0.1\}$ (N = 100) at every angle

From the results presented, we can see that the behavior of both the average beampattern and the time percentage are not far different compared to the results if small number of nodes is utilized in the distributed beamformer. The more nodes we use will give lower sidelobe power in the beampattern, consequently higher probability of sidelobe level lower than P_0. If we examine the average beampattern result, more fluctuation is occurring in the sidelobe power level. We can see that the Euclidean based method and the large sector method still give the best performance compared to the other methods. The other thing worth mentioning is when we significantly increase the number of utilized nodes; the main beam width will not change much. This result shows the proof of the theory studied in [16] where the main beamwidth is only affected by the value of R and independent from N if tha value of N is large. However, when a finite number of nodes is used, the main beam result is dependent on the location of the nodes selected.

V.5. **Impact of location error**

In this section, we will investigate the effect of location error. To acquire the location of the cognitive nodes, each of the nodes sends a message to the cluster head containing their location. In this process of information exchange, error of information may occur due to interference and noises. Other source of location error is when the cognitive nodes acquire their own location through the GPS system. As described in the previous section that GPS localization have certain degrees of error, and these location errors will affect the beampattern. We also consider the location error of the destination, since the main beam of the beampattern is designed to cover the location of the destination. We will present the result of distributed beamforming in cognitive radio with the presence of localization error.

For the location error scenario, we model the location error as follows:

$$\widehat{r_k} = r_k + \Delta r_k \qquad \text{V-3}$$

$$\widehat{\psi_k} = \psi_k + \Delta \psi_k \qquad \text{V-4}$$

Where Δr_k and $\Delta \psi_k$ denote the error value on the node location, $(\widehat{r_k}, \widehat{\psi_k})$ denotes the node location information after the error addition, and (r_k, ψ_k) denote the accurate location of the kth node. In this work, we model the error as random variables following the Gaussian distribution with $\mu = 0$ and

$$\sigma_{r_k}^2 = 0.05R \text{ for } \Delta r_k \left(\Delta r_k \sim N(0, 0.05R) \right)$$

$$\sigma_{\psi_k}^2 = 0.1 \times 2\pi \text{ for } \Delta\psi_k \ (\Delta\psi_k \sim N(0, 0.1 \times 2\pi))$$

We compare the result of distributed beamforming in cognitive radio network with the presence of location error and without error.

By comparison of the figure V-10 and V-11, we can see that when location error is considered, the width of the mainbeam increases in general. Examining the 3-dB beamwidth, Euclidean based method shows an increase of $30,68^\circ$, the ring range shows increase of $27,12^\circ$, large sector method gives an increase of 40°, circle range method gives 60° increase of main beamwidth, and finally the small sector and opposite sector method both give 72° of increase of the main beamwidth. Next we examine the sidelobe level at the angle of 30°. The Euclidean and ring range method show slight increase of power level at the designated angle, the small sector and opposite sector method show large increase of power in that angle (11.9 dB).
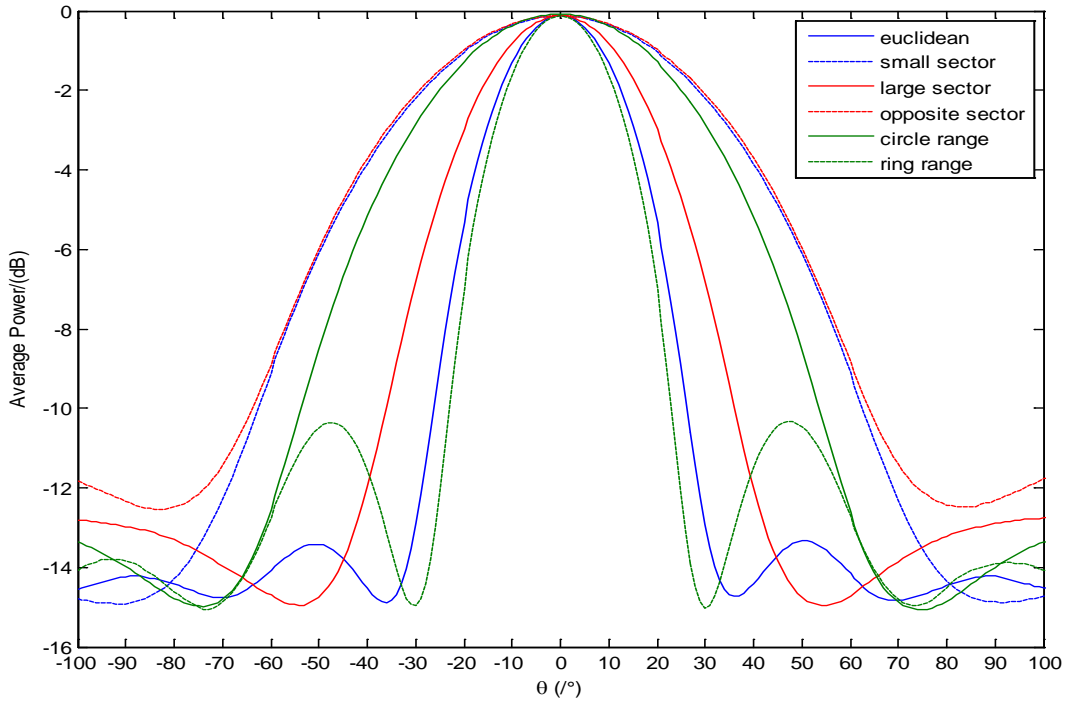
Figure V-10 Average beampattern with $\widetilde{R}$ = 4, N = 17, with location error

The large sector method shows 8 dB increase of power, and the circle range method shows -12 dB of power increase in that angle. Based on the average beampattern analysis, we can conclude that the Euclidean and ring range method is the least sensitive method in the presence of location error which is more preferable to be implemented in the system. While

the small sector, opposite sector, and ring range method are most sensitive to the location error.
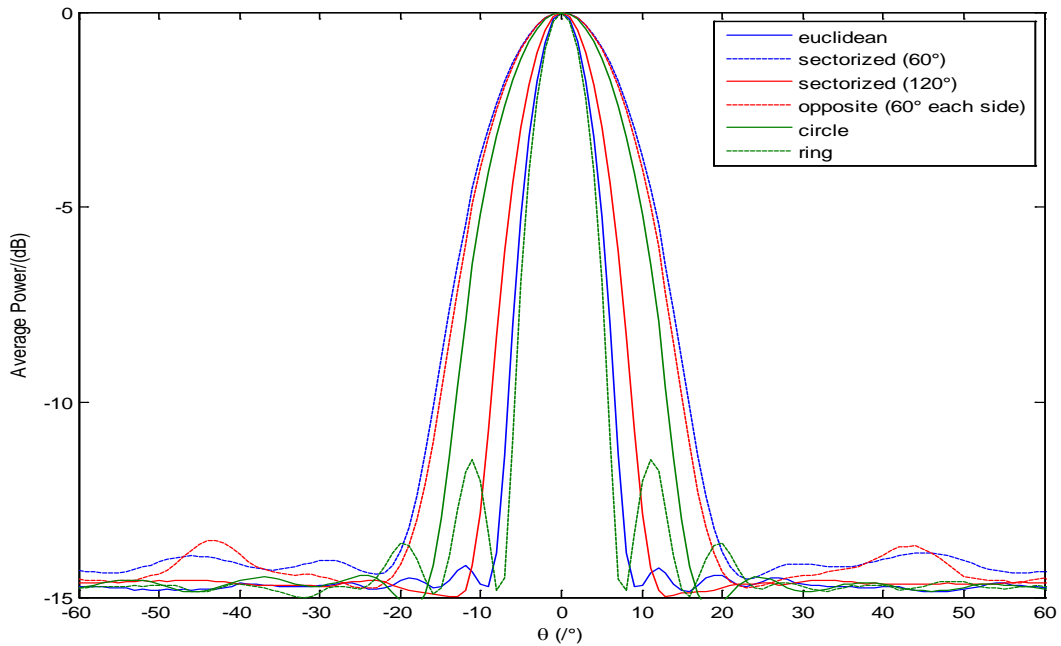

Figure V-11 Average beampattern with $\widetilde{R} = 4$ and N = 17

The next step is to examine the time percentage result of the beampattern generated with the presence of error. We compare the result of time percentage calculation with and without the presence of location error. We can see from the figure that the time percentage of power received at every angle is lower, so that the threshold power is decreasing in general. In other words, the probability that the LU will receive larger power than its threshold is higher with the presence of location error. At the direction of LU, we can see that the Euclidean and ring range method's $t_0(N)$ value is decreased by 10%. While the large sector method at LU direction shows a decrease of almost 70%. The circle range, small sector, and opposite sector method shows the highest sensitivity to the location error.

After the examination, we can conclude that the Euclidean based method is the best node selection method to be applied in the presence of a location error. To fulfill the LU requirements in the presence of node location error, we can also apply the optimal node selection method which will result in the increase of utilized node to cope with the LU requirements.
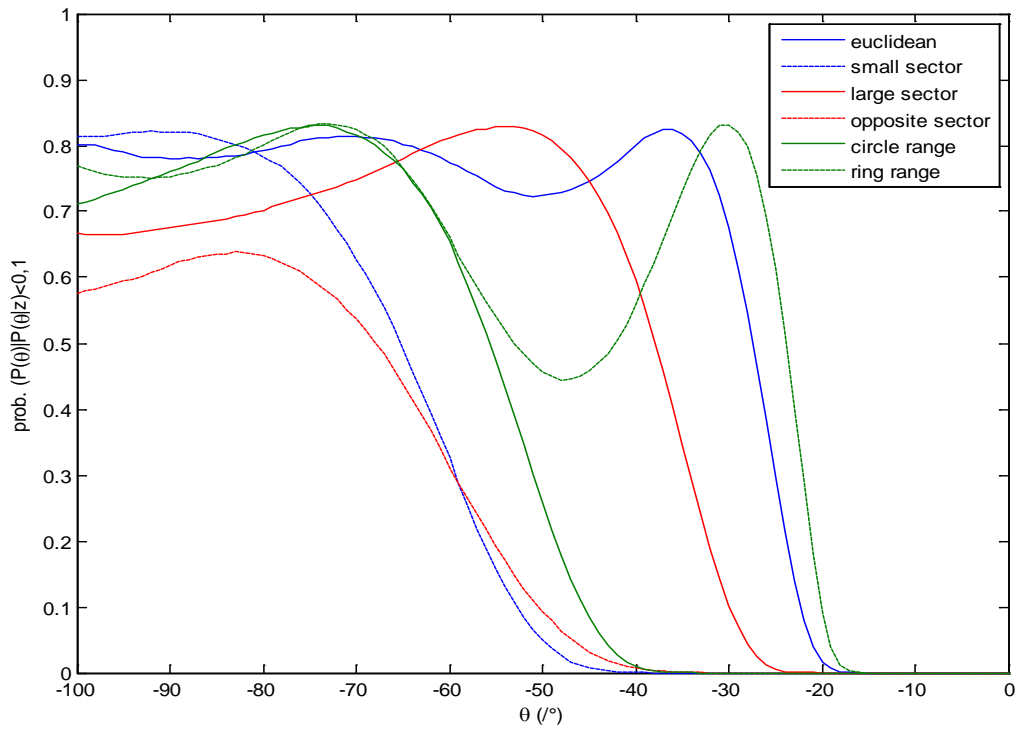
Figure V-12 Time percentage of $\{P(\phi|z_k) < 0.1\}$ (N = 17) with location error
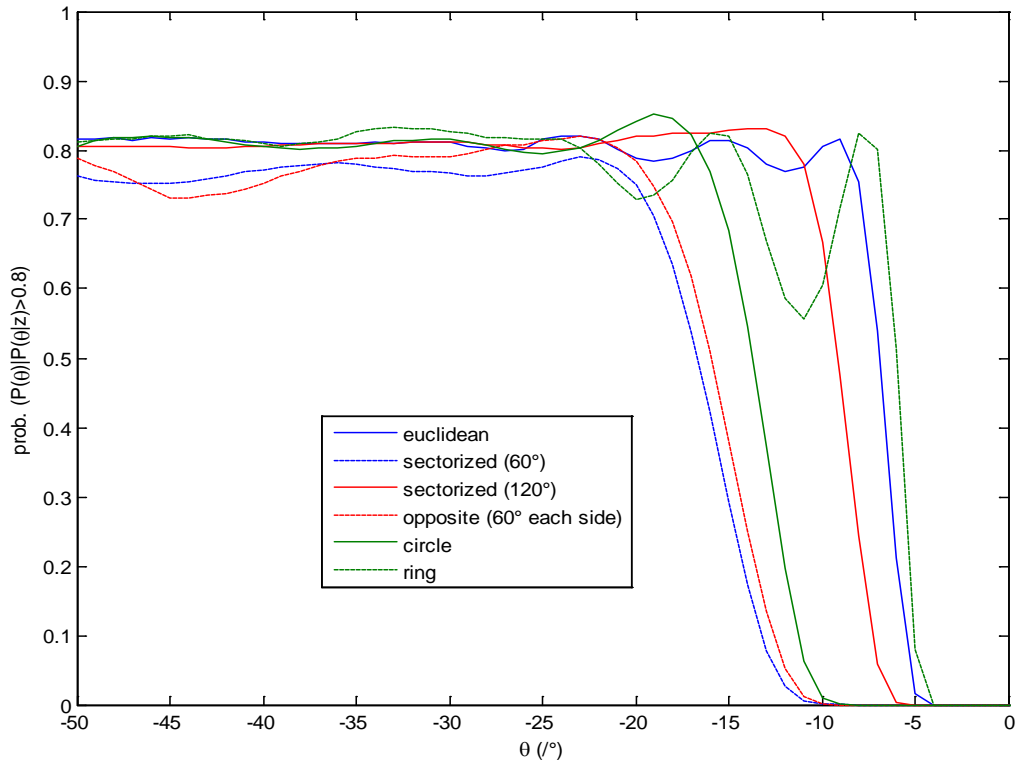

Figure V-13 Time percentage of $\{P(\phi|z_k) < 0.1\}$ (N = 17)

The next important issue which we also consider is the direction error of the destination. The error considered for the destination is the angle error, denoted as:

$$\hat{\phi}_0 = \phi_0 \pm \Delta\phi_0 \qquad \text{V-5}$$

Where $\hat{\phi}_0$ is the angle information after error addition, ϕ_0 is the actual angle, and $\Delta\phi_0$ is the error estimated. We consider the error addition as a random variable which follows the Gaussian distribution with $\mu = 0$ and $\sigma_{\phi_0}^2 = 0.1x\ 2\pi$.

The error of destination direction can be at the area of $2|\Delta\phi_0|$ with ϕ_0 which is the actual direction as center value. We assume that we have a priori knowledge of the destination direction.

We can calculate the -3 dB beamwidth of the average beampattern with no location error from the figure V-14:
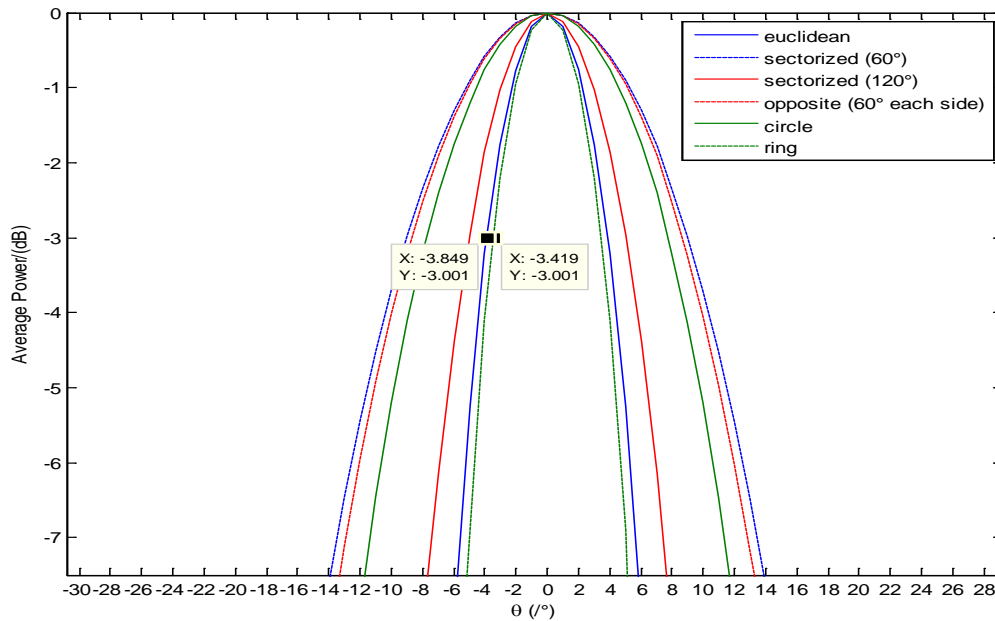
Figure V-14 3-dB beamwidth of DB with $N = 17$, and $\widetilde{R} = 4$

We can see that the main beamwidth of the beampattern using Euclidean based node selection with $\widetilde{R} = 4$, and $N = 17$ is 2 x 3.857 =7.714°. The main beamwidth generated by the beamformer can still cover the possible position of the destination even after error addition. If node location error is taken into consideration, we can see from the previous result that the main beamwidth of the beampattern is enlarged by itself.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

VI.1. **Conclusions**

- Optimal node number selection based on the licensed user requirements algorithm is presented in this thesis work. This work falls in the concept of green communications which has the main goal of energy conservation.

- CDF as one of the selection criterion is presented to show that the probability of the sidelobe power does not exceed the threshold power of licensed user in cognitive radio network. It is an important requirement for the cognitive radio network since it shows the percentage of time that the LU receives interference from other users.

- The novel result of the node number selection method is presented. Taking into account the LU requirements, the optimal node number which should be utilized, in order to generate communication beam using distributed beamforming can be decided.

- Several nodes selection methods are presented in this thesis work: Euclidean based method, sector based method, and circle and ring range method. The result of these different node selection algorithms shows that when the number of utilized nodes is decided, the location of the nodes decides the form of the beampattern.

- From the simulation results, we can conclude that the Euclidean based and the large sector node selection gives the best result regarding the sidelobe power level and CDF of the beampattern.

- After node selection method was applied, location error of the nodes and destination is taken into consideration in the distributed beamforming application for cognitive radio. We model the errors as Gaussian random variables.

- When we define the distance error (Δr_k) to 5% and the direction error ($\Delta \phi_0$) to 10%, the comparison of the results shows that Euclidean based node selection method is less sensitive or is more robust to location error compared to other methods. The 3-dB beamwidth calculation shows that the beampattern generated by DB using Euclidean based node selection method can cover the destination area even with the presence of error.

VI.2. **Recommendations**

This thesis work is based on several assumptions which make the condition as ideal as possible. For future work in this field, the following recommendations are made for more realistic situations:

- To consider the issue of asynchronization of the distributed CR nodes.
- To consider the weights applied to each of the utilized node. In this thesis work, we assume that the weight applied to each CR node is uniform. Applying different weight to CR nodes in order to form a beampattern towards a particular direction is of an interest.
- To consider the effects of multipath-fading or shadowing to the beampattern of DB in CR networks.
- To consider the protocol that should be used by the CR nodes to share the information about their location.
- To consider the process of node clustering in the CR networks, and consequently the protocol to select the cluster head from the distributed nodes.
- To consider different distributions for the location error and the impact of that on distributed beamforming for cognitive radio.

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