Addis Ababa University
Addis Ababa Institute of Technology
School of Electrical and Computer Engineering

Side Lobe Reduction in Equally Spaced Linear Antenna Arrays using Antenna Thinning Technique

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By: Yonas Techale
Advisor: Dr. Murad Ridwan

A thesis submitted to Addis Ababa Institute of Technology, School of Electrical and Computer Engineering in partial fulfillment of the requirements for the degree of Master of Science in Communication Engineering.

November 22, 2023
Addis Ababa, Ethiopia

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Approval by the Board of Examiners

1. Advisor

   Name Signature Date

2. Chairman

   Name Signature Date

3. Internal Examiner

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4. External Examiner

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Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for this thesis have been acknowledged.

Yonas Techale

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Place: Addis Ababa, Ethiopia

Date of submission: September 22, 2023

This thesis has been submitted for examination with my approval as a university advisor.

Dr. Murad Ridwan

Advisor Signature

Abstract

In antenna array design, the radiation pattern is a fundamental performance metric. It is a mathematical or graphical representation of the spatial distribution of radiated energy of an antenna array as a function of directional space coordinates. Array antennas can vary their directivity patterns through amplitude and phase control. One of the most important aspects of an antenna array is reducing interference and radiation power waste. Reduced side lobe level also avoids false target indication. Thinning is a technique for reducing the total number of active elements in an antenna array while maintaining system performance.

This study aims to improve antenna performance by lowering the side lobe level using antenna thinning applying GA. A genetic algorithm achieves optimal solution by simulating the natural selection process. It starts with randomly selected candidates as the first generation. In the beginning, we studied radiation patterns of equally spaced and non-equally spaced linear antenna arrays; and radiation patterns for uniformly spaced, non-uniformly spaced, and non-uniformly spaced with rotated elements array for N=20. It is demonstrated in the result that non-uniform spacing and rotated elements can significantly improve the directivity and reduce side lobes compared to uniformly spaced arrays.

In addition, it is observed in the beam pattern resulting from one typical first-generation candidate that the sidelobe level is lower in the azimuth direction but higher in the elevation direction compared to the full array. The exact sidelobe level and fill rate of the array is then around 8.7 and 71.75% respectively. This means that 71.75% of the array elements are active and the sidelobe level is approximately 9 dB. It needs to be suppressed further by applying a genetic algorithm with 30 generations. Thus, the result shows the sidelobe level and fill rate of the array after applying GA with 30 generations is around 17.38 and 76.5% respectively. Compared to the first-generation candidate, it uses 5% more active elements while achieving an additional 9 dB sidelobe suppression. Compared to the full array, the resulting thinned array can save the cost of implementing T/R switches behind dummy elements, which in turn leads to a roughly 25% saving on the consumed power. Even though the thinned array uses fewer elements, the beamwidth is close to what could be achieved with a full array.

Key words: Antenna thinning, radiation pattern, Side lobe level, GA.

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Last but not least, I would like to extend my deepest gratitude to my dear families for their continuous support and the roles they played on my behalf. My sincere appreciation also goes to my best friends who helped me a lot in many ways for the successful completion of my study. May God bless you all!

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List of Acronyms

AAA	Adaptive Array Antennas
ADCs	Analog-to-digital converters
CGA	Conjugate gradient algorithm
DOA	Direction of arrival
DSP	Digital signal processing
ESLAs	Equally spaced linear arrays
FNBW	First null beamwidth
GA	Genetic algorithm
HPBW	Half power beamwidth
NUSLAs	Non-uniformly spaced linear arrays
PAA	Phased Array Antennas
SLL	Side lobe level
SNR	Signal-to-noise ratio
ULA	Uniform linear array

Chapter One

Introduction

1.1. Background

Antenna arrays are used to improve the performance of wireless communication systems. They can be used to increase the capacity and spectral efficiency of the system, as well as to improve the range and reliability of the communication.

An antenna array is a grouping of two or more antenna elements that are arranged in a specific configuration. The elements of an antenna array can be similar or different, and they can be arranged in a linear, planar, or spherical array. The performance of an antenna array is influenced by several factors, including the geometry of the array, the spacing between the elements, the amplitude and phase of the excitation signal, and the environment in which the array is operating [1]. A single antenna element has a relatively broad radiation pattern and provides low values of directivity (gain). In many applications, antennas with very directive characteristics (very high gains) are required to meet the demands of long-distance communication. This can only be achieved by increasing the electrical size of the antenna. As a result, the performance of a single-element antenna is somewhat limited. Antenna arrays are used to achieve high directivity, narrow beamwidth, low side lobes, point-to-point, preferred coverage pattern characteristics, and so on [2]. Closely spaced antenna elements can allow for steerable beam features and a small physical space for the overall array. However, it can also introduce unwanted mutual coupling effects and side lobes. These undesirable features can degrade array performance.

Thinning is a technique for reducing the number of active elements in an antenna array while maintaining system performance. This can be done by removing (or "thinning") some of the elements from the array without significantly changing its beamwidth or main lobe gain. Thinning is most effective when the main beam is narrow and the demand for control of radiations outside the main beam is low.

The primary concern in thinned array design is determining the best set of elements spacing to meet array specifications. This can be a difficult task, as many possible combinations of element spacing could be used. In the past, many different approaches to thinned array design have been proposed, including analytical methods, numerical methods, and heuristic methods.

In recent years, non-gradient-based optimization methods such as genetic algorithms, the ant colony technique, and particle swarm optimization have proven to be particularly effective for thinned array design. These methods can search through the space of possible element spacing and find the best set of spacing that meets the array specifications [3]. In this thesis, we studied the side lobe reduction using antenna thinning by applying a genetic algorithm approach.

1.2. Statement of the Problem

Uniformly excited, equally spaced linear arrays (ESLAs) have a side lobe level that is too high for many applications. This can lead to unwanted radiation patterns, energy waste, and a reduction in overall antenna performance. The goal of this thesis is to investigate the use of a new method for antenna thinning that is specifically tailored to ESLAs. The new method is based on randomly removing elements from the original array and then evaluating each thinned array by calculating its side lobe level and gain. The thinned array with the lowest side lobe level that does not significantly reduce the gain of the original array is selected. The new method will be evaluated using simulation results and compared to the results of other methods for antenna thinning. The thesis will conclude by discussing the implications of the results and the future directions of research in antenna thinning.

1.3. Objective and Scope of the Thesis

1.3.1. General Objective

The central aim of this thesis work is to reduce the side lobe level in equally spaced linear arrays (ESLAs) using antenna thinning techniques.

1.3.2. Specific Objective

In light of this general objective, the research will have the following specific objectives:

- ✓ To study the effect of non-uniform amplitude and uniform spacing linear arrays over the uniform amplitude and spacing linear arrays.
- ✓ To examine the effect of varying the number of arrays and array element spacing based on angle separation.
- ✓ To find the best antenna element position/inter-element spacing using thinning techniques.

- ✓ To study and compare the radiation patterns of equally spaced and non-equally spaced linear antenna arrays.
- ✓ To compare the non-thinned radiation patterns of equally spaced linear antenna arrays with the thinned ones.

1.4. Scope of the Study

The scope of this study is to develop and evaluate a new antenna thinning technique for equally spaced linear antenna arrays (ESLAs) using MATLAB software. The new technique will be designed to reduce the side lobe level of ESLAs while maintaining or improving the gain of the array. The technique will be evaluated using MATLAB simulations with a variety of ESLAs. The results of the simulations will be used to assess the performance of the new technique and to identify the parameters that have the greatest impact on the side lobe level. The findings of this study will contribute to the development of more efficient and effective antenna thinning techniques for ESLAs.

1.5. Methodology

To attain the objectives of the research, the methods to be employed are:

1. **Literature review**:
   - ✓ We reviewed the existing literature on antenna thinning to identify gaps in the research. We found that there is a lack of research on the use of genetic algorithms for antenna thinning. We decided to address this gap by conducting my research on the use of genetic algorithms for antenna thinning.
   - ✓ We searched for relevant articles and books on antenna thinning. We read and took notes on the different antenna thinning techniques that were discussed. We summarized the key findings of the articles and books in a written report.
   - ✓ We reviewed the different antenna thinning techniques that have been proposed in the literature and discussed the advantages and disadvantages of each technique. We considered the different types of antenna thinning techniques, such as element removal, and genetic algorithms. We discussed the advantages and disadvantages of each technique in terms of side lobe level reduction, gain, and complexity.

2. **System modeling:**
   - ✓ We developed a mathematical model of the thinned antenna system that we would be using in my simulations. We defined the variables and parameters of the system and wrote a mathematical model of the system. We verified the model by comparing the results obtained to the results of other studies.
   - ✓ We discussed the parameters that we would be varying in my simulations and how these parameters affected the performance of the system. We considered parameters such as the number of elements, the element spacing, and the weighting factor. We discussed how these parameters affected the side lobe level, gain, and complexity of the thinned antenna system.
3. **Simulation:**
   - ✓ We used MATLAB to simulate the thinned antenna system. we varied the parameters of the system and observed how the performance of the system changed. We also compared the results of my simulations to the results of other studies.
   - ✓ We analyzed the results and identified the optimal parameters for the thinned antenna system.
4. **Analysis and Interpretation of the results:**
   - ✓ We discussed the results of my simulations and compared them to the results of other studies. We compared the side-lobe level reduction and gain of my thinned antenna system to other techniques. We discussed the implications of my results for the design of thinned antenna systems. We discussed how my results can be used to improve the performance of thinned antenna systems in different applications.

1.6. Review of related works

Researchers have conducted and are still conducting studies to investigate reasonable ways to improve the performance of antenna arrays. So far, much research has been conducted on different aspects of obtaining high directivity, low side lobes, narrow beamwidth, and preferred coverage of array antennas. In most of the previously conducted studies, researchers considered different parameters such as the spacing between individual array elements, the excitation amplitude, the excitation phase, and the array geometry. They used these parameters individually or in combination with some or all of them to improve the performance of antenna arrays. The spacing between array elements can be designed to be uniform or non-uniform, depending on the researcher's preference, the required application, and the expected outcome. A short literature survey of some selected papers is presented here.

H. Oraizi and M. Fallahpour in [4] proposed a method for designing non-uniformly spaced linear arrays (NUSLAs) with fixed first null beamwidth (FNBW) and minimum side lobe levels (SLLs). They used a combination of genetic algorithm (GA) and conjugate gradient algorithm (CGA) to optimize the design parameters of the NUSLAs.

The authors first derived the relationship between SLL, FNBW, and the number of elements in a NUSLA. They then used this relationship to design NUSLAs with the minimum possible SLL for a given number of elements and FNBW. They also designed NUSLAs with specified directivity and tolerable SLL. The authors compared the performance of NUSLAs with equally spaced linear arrays (ESLAs) with uniform excitation. They found that NUSLAs outperformed ESLAs for wider average element spacing. The authors also designed a parallel half-wavelength dipole array for specified FNBW and minimum achievable SLL. They then designed the array with a constraint on the minimum distance between elements for specified directivity and SLL.

The authors concluded that NUSLAs are a promising approach for improving the performance of antenna arrays in terms of SLL, FNBW, and directivity. They also suggested that NUSLAs could be used in applications where narrow beamwidth and low SLL are important, such as radar and satellite communications.

Dr. Murad Ridwan in [5] studied design of Non-Uniform Antenna Arrays. This paper proposes a method for designing non-uniform antenna arrays using a genetic algorithm (GA). The GA is used to optimize the element spacing of the array to achieve a desired side lobe level and beamwidth. The authors compare the performance of the proposed method with that of uniform and Dolph-

Chebyshev arrays. They show that the non-uniform array designed using GA has a lower side lobe level and a narrower beamwidth than the other two arrays.

P. Joshi in [6] proposes a method for optimizing the weights of the elements in an antenna array using a genetic algorithm (GA). The GA is used to minimize the side lobe levels of the array while maximizing its directivity. The authors compare the performance of the proposed method with that of a conventional method based on an exhaustive search. They show that the GA-based method can achieve significantly better results.

A study carried out by A. Khalid and S.A. Sheikh proposes a method for optimizing the amplitude distributions of the elements in a linear antenna array using a genetic algorithm (GA). The GA is used to minimize the side lobe levels of the array while maintaining its directivity. The authors compare the performance of the proposed method with that of a conventional method based on an exhaustive search. They show that the GA-based method can achieve significantly better results [7].

S. Ogurtsov and S. Koziel in [8] propose a method for reducing the side lobe levels of a uniformly spaced broadside linear array by using non-uniform excitation. The non-uniform excitation is generated using a genetic algorithm (GA). The authors compare the performance of the proposed method with that of a conventional method based on uniform excitation. They show that the non-uniform excitation method can achieve significantly better results.

T.S. Joey Leaseetha and Dr. R.Sukanesh in [9] propose a method for synthesizing the radiation pattern of an antenna array using a genetic algorithm (GA). The GA is used to optimize the weights of the elements in the array. The authors compare the performance of the proposed method with that of a conventional method based on an exhaustive search. They show that the GA-based method can achieve significantly better results.

A study conducted by Manuel Fernández Delgado in [10] proposes a fast method for array thinning based on genetic algorithms (GA). The proposed method uses a simplified model of the far-field pattern to accelerate the evaluation of the fitness function. The authors compare the performance of the proposed method with that of a conventional GA. They show that the proposed method can achieve significant speedup without sacrificing accuracy.

Manica Luca, and Rocca Paolo in [11] present different procedures for designing sub-arrayed antennas using genetic algorithms (GA). The proposed procedures can be used to design sub-arrays with unequal sizes and weights. The authors compare the performance of the proposed procedures with that of other state-of-the-art methods. They show that the proposed procedures can achieve good performance with low computational complexity.

Table 1.1 shows the summarized of the above existing research for genetic algorithms with significantly improved performance, as well as they have some limitations in their works. Table 1.1 below summarizes the review of the works of [4, 6, 12].

Table 1.1: Summary of related works

Authors	Problem	Techniques	Limitations
P. Joshi and R. Dubey [6]	Improving the antenna array's performance is needed (improve the directivity)	✓ Apply Genetic algorithm ✓ Single-point crossover mutation	Not utilize a small number of antenna elements
H. Oraizi and M. B. Fallahpour [4]	Designed of NUSLA for fixed N and BW is required to have the minimum possible SLL	✓ Use the combination of GA-CG as an optimizer ✓ Use Neural Network model for the calculation of S-parameters and coupling among elements	They only design dipole arrays for specified directivity and SLL
G. K. Mahanti [12]	Finding new technique for designing a thinned linear antenna array with fixed side lobe level and a fixed percentage of thinning	✓ Apply real-coded genetic algorithm	Not use terminating criteria to the total number of side lobe calculations

All of these papers have shown that genetic algorithms can be an effective tool for designing antenna arrays with improved performance. The GA can be used to optimize a variety of parameters, including the element spacing, the element amplitude distributions, and the element weights. The GA can also be used to synthesize the radiation pattern of an antenna array.

1.7. Contribution of the Thesis

The work proposes a new method for designing non-uniform linear arrays using genetic algorithms. The proposed method is shown to be effective in achieving low side lobe levels while maintaining good directivity. And also, this proposed method is shown to be effective in achieving multiple design goals, such as low side lobe levels, good directivity, and a specified number of elements.

Overall, the work makes significant contributions to the field of antenna array design. The proposed methods are effective in achieving low side lobe levels while maintaining good directivity and meeting multiple design constraints. The work also provides new insights into the use of genetic algorithms for antenna array design.

1.8. Thesis Organization

The remainder of the thesis is organized as follows: introduction of the research, the statement of the problem, objectives of the thesis, methods being followed to complete the research, and review of the related works are conducted in chapter 1. Chapter 2 will provide a fundamental background on antennas and antenna arrays. Chapter 3 will discuss the Thinning Linear Antenna Arrays and provide a brief introduction to genetic algorithms and their use in the design of non-uniform antenna arrays. Chapter 4 will summarize the main results of the thesis and discuss their implications. Finally, Chapter 5 will provide conclusions based on the results obtained and recommendations for future work.

Chapter Two

Fundamentals of Antenna and Antenna Arrays

2.1. Introduction

In the previous chapter, the introduction and literature review of works related to antenna thinning and genetic algorithms for Equally Spaced Linear Array and non-uniformly spaced linear array elements were briefly discussed. In this chapter, the basics of antenna, antenna array, and signal model of the uniform linear array are discussed.

The chapter is organized as follows.

In section 2.2 fundamentals of an antenna and a brief discussion of basics of antenna parameters are provided. In section 2.3 antenna arrays and signal model of uniform linear array along with its system model are described. The basic parameters of antenna arrays such as array factor, beam steering, array geometry, and element spacing briefly described in section 2.4. Finally, the types of antennas based on their purpose are discussed in section 2.5.

2.2. Basics of antenna

An antenna, as defined by Balanis in [1] is an essential component in wireless communication systems. It is a transducer that converts guided electromagnetic waves from transmission lines to unrestricted waves in free space in its transmission mode and converts free space waves to guided waves in its reception mode. It exhibits reciprocity, which means that an antenna maintains the same characteristics whether transmitting or receiving. An antenna is typically required in an advanced wireless system to optimize or enhance radiation energy in some directions while diminishing it in others. As a result, the antenna must be both exploratory and investigative in nature. Antennas are available in a wide range of shapes and configurations. One of the basic theoretical radiators, the isotropic point source radiator, is useful because it can be used as a reference for other antennas. In free space, an isotropic point source radiates equally in all directions. Antennas are categorized into three types based on their shape: linear, planar, and circular. Some basic parameters that apply to all types of antennas are defined here.

2.2.1. Radiation pattern

One of the most important characteristics of an antenna is its radiation pattern. The radiation pattern is a graphical representation of the power radiated by the antenna as a function of direction. It is typically represented as a two-dimensional plot, with the horizontal axis representing the azimuth angle and the vertical axis representing the elevation angle [1].

The radiation pattern of an antenna can be divided into two main parts: the main lobe and the side lobes. The main lobe is the region where the antenna radiates the most power. The side lobes are the regions where the antenna radiates less power. The side lobes are often undesirable, as they can interfere with other signals. The level of the side lobes is an important factor in antenna design. A low side lobe level is desirable, as it means that the antenna will not interfere with other signals as much. There are a number of techniques that can be used to reduce the side lobe level of an antenna, such as tapering the antenna elements or using a more complex antenna design [1].

The radiation pattern of an antenna is also important for determining the antenna's directivity. Directivity is a measure of how well an antenna concentrates its radiation in a particular direction. A highly directional antenna will have a narrow radiation pattern, with most of the power radiated in a single direction. A less directional antenna will have a wider radiation pattern, with the power radiated more evenly in all directions. The directivity of an antenna is important for a number of applications, such as radar and satellite communications. In radar, a highly directional antenna is used to focus the radar beam on a target. In satellite communications, a highly directional antenna is used to link the satellite to a ground station.

The bellow figure represents the radiation pattern of a dipole antenna [1].

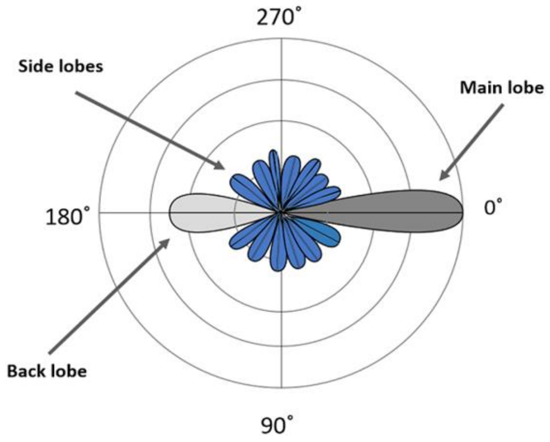

Figure 2.1:Radiation pattern of a dipole antenna

2.2.2. Beam width

The beamwidth of an antenna is a measure of how directional the antenna is. It is defined as the angular distance between the points on either side of the main lobe where the power radiated by the antenna is half of its maximum value. The beamwidth is typically measured in degrees.

The beamwidth of an antenna can be affected by a number of factors, including the type of antenna, its size, and its frequency. For example, a Yagi-Uda antenna has a narrower beamwidth than a dipole antenna. The beamwidth of an antenna is important for a number of applications. For example, a narrow beamwidth is desirable for radar antennas, as it allows the radar to focus its beam on a target. A wider beamwidth is desirable for antennas used for broadcasting, as it allows the signal to be received by a wider range of receivers. The beamwidth of an antenna is also related to its directive gain. Directive gain is a measure of how much power an antenna radiates in a particular direction compared to an isotropic antenna. A higher directive gain means that the antenna radiates more power in a particular direction, and therefore has a narrower beamwidth [1].

In general, the beamwidth of an antenna and its directive gain are inversely proportional. This means that as the beamwidth decreases, the directive gain increases. However, there is a limit to how narrow the beamwidth can be, as the antenna will eventually become too directional and will not be able to radiate power in all directions.

2.2.3. Side lobes and nulls

No antenna can radiate all of its energy in a single preferred direction. Some energy will always be emitted in other directions at lower levels than the main lobe. Side lobes are smaller peaks that are commonly specified in dB down from the main lobe [1].

The level of the side lobes and nulls is an important factor in antenna design. A low side lobe level and a narrow null width are desirable, as they mean that the antenna will not interfere with other signals as much. There are a number of techniques that can be used to reduce the side lobe level and null width of an antenna, such as:

- ✓ Tapering the antenna elements: This involves making the antenna elements smaller towards the edges of the antenna. This reduces the amount of energy that is radiated in the side lobes.

- ✓ Using a more complex antenna design: This can involve using multiple antenna elements or using a more sophisticated antenna shape. This can further reduce the side lobe level and null width.

2.2.4. Bore sight

The antenna bore sight is the physical aiming direction or location where the radiation pattern must be maximized. In other words, it is the normally intended maximum radiation direction. The bore sight of an antenna can be adjusted by changing the physical orientation of the antenna. This can be done by rotating the antenna, tilting the antenna, or both. The bore sight can also be adjusted by using an electronic beam steering system.

2.2.5. Directivity and Gain

- ➢ **Directivity**: Directivity is the term used to describe how well an antenna can focus its radiated power in a specific direction. It indicates the antenna's capability to concentrate energy into a particular beam or pattern. Directivity is usually measured in decibels (dB) and is determined by the antenna's radiation pattern. A higher directivity value suggests that the antenna emits more power in a specific direction [1].Generally, Directivity is about how well an antenna focuses its power in a specific direction. It tells us how much power is concentrated in that direction compared to other directions.
- ➢ **Gain**: Gain measures how effectively an antenna converts input power into radiated power in a particular direction. It compares the antenna's power in that direction to a hypothetical antenna that radiates power equally in all directions [1]

2.2.6. Polarization

Polarization is defined as the orientation of an electromagnetic wave's electric field. Polarization is typically represented by an ellipse. Linear polarization and circular polarization are two types of elliptical polarization. The antenna determines the initial polarization of a radio wave [1].

Chapter Three

Thinning Linear Antenna Arrays with Genetic Algorithm Optimization

3.1. Introduction to antenna arrays

Single antennas are not very directive and have low gain. To achieve good directivity (high gain), the electrical size of the antenna must be increased. Increasing the size of a single element results in more directive properties. However, there is a better way to increase antenna dimensions without increasing the size of individual antennas. This is done by assembling radiating elements in different geometrical shapes. An antenna array is a collection of elements in a specific shape. Array elements are typically identical, but they can be different. If they are different, the design becomes more complicated [1].

3.1.1. Total field for antenna array

The total field of an antenna array is calculated by adding the vectors of the fields radiated by each element. In an ideal case, the currents of each element would be the same, but this is not usually possible. For directive patterns, the fields from the array's elements must interfere constructively in the desired directions and destructively in the remaining directions. Constructive interference occurs when the fields from different elements add together to produce a larger field, while destructive interference occurs when the fields from different elements cancel each other out.

Five controls can be used to achieve the overall pattern of an antenna array. The first is the geometrical configuration of the array, which refers to its shape. The shape can be linear, circular, rectangular, planar, or any combination of these. The second control is the relative displacement of the elements, which means the distance between them matters. The last three controls are the excitation amplitude, phase, and relative pattern of the individual elements.

The total field of an antenna array is equal to the field of a single element at the origin multiplied by an array factor. The array factor varies with the shape, amplitude, spacing, and phase of the array. When the elements are identical, meaning they have the same radiated field, the simplest way to calculate the total field of the array is to use the antenna array multiplication rule. This rule states that the radiation for a total array, Et, can be calculated by multiplying the radiation field of a single antenna, E1, by the array factor, A.

$$\mathrm{E}_{\mathrm{t(total)}} = [\mathrm{E}_{\mathrm{r}}(\text{Single element at reference point})] * [\text{Array factor}] \qquad (3.1)$$

If the elements of an antenna array are identical and have the same spacing, the array factor simplifies. The array factor is determined by the number of elements, their geometrical arrangement, their relative magnitudes and phases, and their spacing [1].

3.1.2. Conventional Antenna Array

In terms of the geometrical arrangements of the elements, an antenna array can be classified into three main categories: linear arrays, planar arrays, and circular arrays. However, in this thesis, only the case of linear arrays is considered due to its simple structure and better physical demonstration. A linear array is one of the simplest array geometries, with the antenna element centers aligned along a straight line [13].

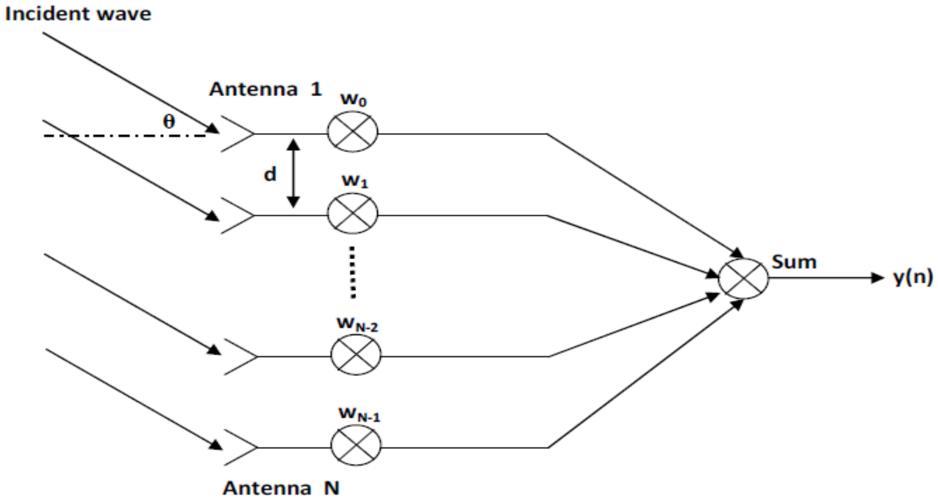

Figure 3.1: Uniform amplitude N-element linear array with equal spacing

3.1.2.1. Linear array

Linear arrays are one of the simplest and most practical array geometries. They consist of individual radiating antenna elements aligned in a straight line with uniform inter-element spacing. Single antennas typically have wide radiation patterns, which results in low directivity (gain). Linear arrays offer better directivity than single antennas with expansion because the elements in a linear array can be arranged in such a way that the radiation patterns of the individual elements add constructively in the desired direction and destructively in the undesired directions. The simplest type of linear array is a uniform linear array (ULA), which consists of elements with the same amplitude and are spaced uniformly. The phase of the current in each element is progressive, meaning that it leads to the phase of the current in the element before it. The amount of phase lead is proportional to the distance between the elements. ULAs are often used in applications where high directivity is required, such as radar and satellite communications [1].

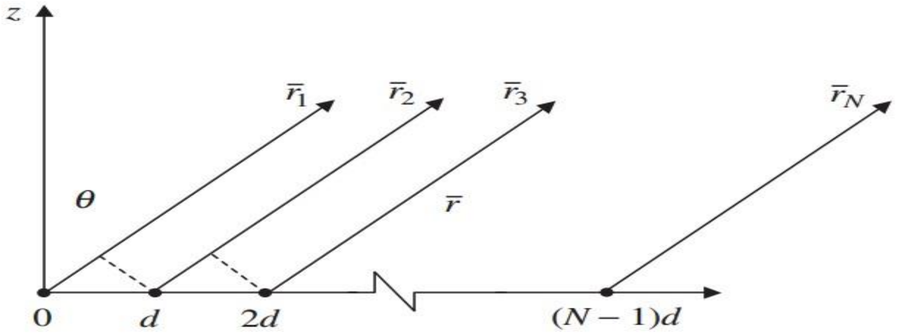

Figure 3.2: uniform N-element linear antenna array geometry with each consecutive element spaced with a distance d [14]

Here, in the above figure showing N elements of linear array, it is assumed that the n^{th} element leads $(n\text{-}1)^{th}$ element by an electrical phase shift of δ radians which can be achieved by shifting the phase of the antenna current of each radiating elements.

$$AF = 1 + e^{j(kd*sin\theta+\delta)} + e^{j2(kd*sin\theta+\delta))} + \cdots + e^{j(N-1)(kd*sin\theta+\delta)} \qquad (3.2)$$

In which:

θ is the angle measured from the z axis -

d is the inter-element spacing

δ is electrical phase difference between two adjacent radiating elements

The array factor series of equation (3.2) above can be more precisely described by

$$\sum_{n=1}^{N} e^{j(n-1)(kd*sin\theta+\delta)} = \sum_{\mathrm{n=1}}^{\mathrm{N}} \mathrm{e}^{\mathrm{j(n-1)*\varphi}} \qquad (3.3)$$

In which $\psi = \mathrm{kdsin}(\theta) + \delta$.

3.2. Basic parameters of antenna array

3.2.1. Array factor (AF)

For an array of N elements, the array factor is given by:

$$\mathrm{AF} = \sum_{n=1}^{N} e^{j(n-1)\Psi} \qquad (3.4)$$

Where $\Psi = kd * \sin\theta + \delta$, k = 2π/λ is the propagation constant, δ is the progressive phase delay between each array element and θ is the incident angle.

The normalized array factor is given by:

$$\mathrm{AF}(\theta) = \frac{\sin\left(\frac{N}{2}\Psi\right)}{N\sin\left(\frac{1}{2}\Psi\right)} \qquad (3.5)$$

3.2.2. Array geometry and element spacing

The spacing between antenna elements is critical when designing an antenna array. If the elements are spaced more than half a wavelength apart, grating lobes will occur in the radiation pattern. These are unwanted side lobes that can reduce the quality of the antenna array.

Another phenomenon that can limit the spacing between antenna elements is mutual coupling. This occurs when the radiation from one element affects the radiation from another element. This can lead to interference between the elements, which can also degrade the quality of the antenna array [15]. The ideal spacing between antenna elements is a compromise between avoiding grating lobes and minimizing mutual coupling. In most cases, the spacing should be between a quarter and a half wavelength apart.

3.3. Uniform amplitude and spacing linear array

A uniform amplitude and spacing linear array is an antenna array where all the elements have the same amplitude and are spaced equally apart [4]. This type of array is often used in radar and communications applications because it provides a high gain and narrow beamwidth.

A uniform amplitude and spacing linear array can achieve a high gain and narrow beamwidth because the individual elements of the array add together constructively in the desired direction. This is because the waves emitted by each element are in phase with each other. The phase of a wave is a measure of how far along its cycle it is. When two waves are in phase, they add together to create a wave with a larger amplitude.

The spacing between the elements of a uniform amplitude and spacing linear array is also important for achieving a high gain and narrow beamwidth. The closer the elements are spaced together, the more concentrated the radio waves will be in the desired direction. However, if the elements are spaced too close together, they may start to interfere with each other destructively. This will reduce the gain and widen the beamwidth of the array.

Here is the generalized form of the N-element antenna linear array:

Let us assume each element is an isotropic source and the element spacing is a half wavelength. An incident wave impinges on the linear array, and the total radiation pattern or array factor (AF) can be obtained by the summation of each element as given by [1]:

$$\mathrm{AF} = 1 + e^{j(kd*\mathrm{sine}\theta+\delta)} + e^{j2(kd*\sin\theta+\delta))} + \cdots + e^{j(N-1)kd*\sin\theta+\delta)}$$

$$= \sum_{n=1}^{N} e^{j(n-1)kd*\sin\theta+\delta} \qquad (3.6)$$

The normalized array factor can be reduced to:

$$\mathrm{AF} = \sum_{n=1}^{N} e^{j(n-1)\Psi} \qquad (3.7)$$

Where$\Psi = kd * \sin\theta + \delta$, k = 2π/λ is the propagation constant, δ is the progressive phase delay between each array element and θ is the incident angle against the horizontal line.

Therefore, multiplying both sides of eq (2.4) bye^{Ψ}, it can be written as

$$(\mathrm{AF})e^{j\Psi} = e^{j\Psi} + e^{2j\Psi} + e^{3j\Psi} + \cdots + e^{(N-1)j\Psi} + e^{Nj\Psi} \qquad (3.8)$$

Subtracting eq (3.7) from (3.8),

$$\mathrm{AF}\left(e^{j\Psi} - 1\right) = -1 + e^{Nj\Psi} \qquad (3.9)$$

Which can also be written as,

$$\mathrm{AF} = [\frac{e^{Nj\Psi} - 1}{e^{j\Psi} - 1}]$$

$$= e^{j[(N-1)/2]\Psi}[\frac{e^{j(\frac{N}{2})\Psi} - e^{-j(\frac{N}{2})\Psi}}{e^{j(\frac{1}{2})\Psi} - e^{-j(\frac{1}{2})\Psi}}]$$

$$= e^{j[(N-1)/2]\Psi}\left[\frac{\sin\left(\frac{N}{2}\Psi\right)}{\sin\left(\frac{\Psi}{2}\right)}\right] \qquad (3.10)$$

If the reference point is the physical center of the array, the array factor of the above equation reduces to:

$$\mathrm{AF} = \frac{\sin\left(\frac{N}{2}\Psi\right)}{\sin\left(\frac{\Psi}{2}\right)} \qquad (3.11)$$

For a small value of Ψ, the above expression can be approximated by,

$$\mathrm{AF} = \frac{\sin\left(\frac{N}{2}\Psi\right)}{\frac{\Psi}{2}} \quad (3.12)$$

the normalized array factor can be reduced to:

$$\mathrm{AF}(\theta) = \frac{\sin\left(\frac{N}{2}\Psi\right)}{N\sin\left(\frac{1}{2}\Psi\right)} \quad (3.13)$$

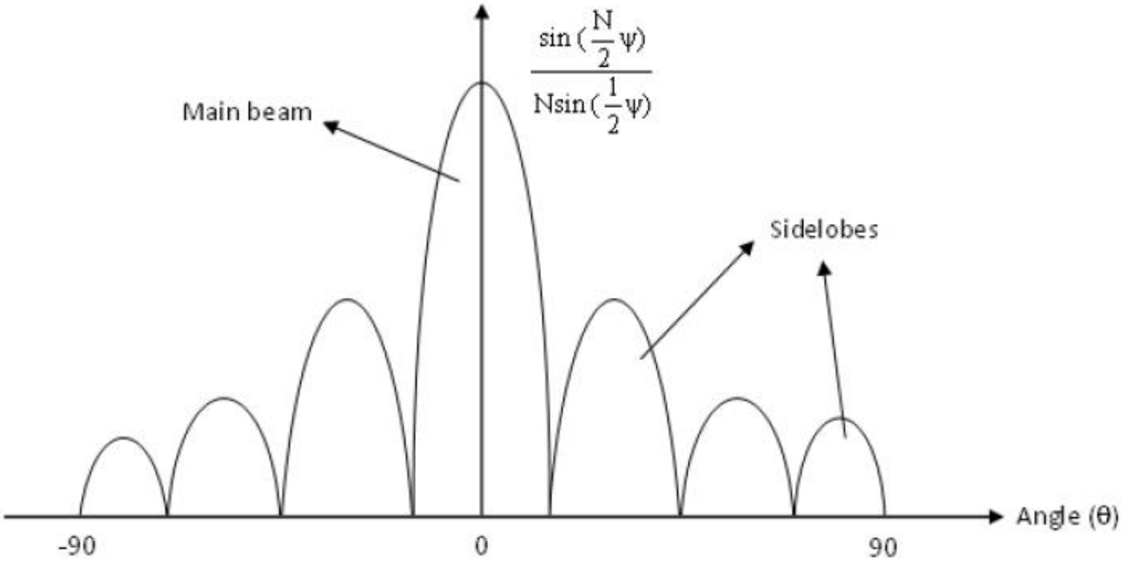

Figure 3.3: Corresponding radiation pattern of equation (3.13)

The figure shows a linear array of N antenna elements, each of which is spaced d apart. The elements are excited by currents of equal amplitude but with different phases. The phase of the current in each element is determined by its position in the array.

The radiation pattern of the linear array is determined by the amplitude and phase of the currents in the individual elements. The amplitude of the radiation pattern is maximum in the direction of the array's main beam. The width of the main beam is determined by the spacing between the elements. From the above the maximum value occurs when $\Psi = 0$ or $\sin\theta = 0$. In this thesis, all the numerical examples are simulated using MATLAB software, which is a matrix computing software designed for numerical modeling.

3.4. Non-uniform amplitude and uniform spacing linear array

A non-uniform amplitude and uniform spacing linear array is an antenna array where the elements have different amplitudes but are spaced equally apart. This type of array is often used in radar and communications applications where it is desired to have a specific radiation pattern.

In a non-uniform amplitude and uniform spacing linear array, the different amplitudes of the elements are used to control the shape of the radiation pattern. For example, if the elements are all excited with the same phase, but have different amplitudes, the radiation pattern will have a main lobe in the direction of the strongest element. The side lobes of the radiation pattern will also be affected by the amplitudes of the elements.

The spacing between the elements of a non-uniform amplitude and uniform spacing linear array is also important for controlling the shape of the radiation pattern. The closer the elements are spaced together, the narrower the beamwidth of the radiation pattern will be. However, if the elements are spaced too close together, they may start to interfere with each other destructively. This will reduce the gain and widen the beamwidth of the array [4].

Some systems demand much lower side lobe levels below the main beam to reduce the level of interference. In this section, we will examine three different types of well-known antenna arrays: binomial, Dolph-Chebyshev, and Taylor distribution. The array factor of a non-uniform amplitude linear array with half-wavelength spacing can be written as:

$$\mathrm{AF}(\theta) = \mathrm{W}_0 1 + \mathrm{W}_1 e^{j(kd\sin\theta+\beta)} + \mathrm{W}_2 e^{j2(kd\sin\theta+\beta))} + \cdots + \mathrm{W}_{N-1} e^{j(N-1)kd\sin\theta+\beta)} = \sum_{n=0}^{N-1} \mathrm{W}_n e^{jnkd\sin\theta+\beta)} \qquad (3.14)$$

where W_n represents the array element coefficients or array excitation amplitudes.

3.5. Beam steering in linear arrays

3.5.1. Beam Steering

Moving the array mechanically allows the beam to be pointed in different directions for a given array. This is referred to as mechanical steering. Beam steering can also be achieved by delaying the signals before combining them. There is no mechanical movement during the process, which is known as electronic steering. Phase shifters are used to change the phase of signals before combining them for narrowband signals. When digital processing is used, signals from various elements can be sampled, stored, and summed after appropriate delays to form beams. The required delay is achieved by selecting samples from different elements and taking them at different times. Each sample is delayed by an integer multiple of the sampling interval; thus, when using this technique, a beam can only be pointed in certain directions.

Beam steering in linear arrays is the process of changing the direction of the main lobe of the radiation pattern of an antenna array. This can be done by changing the phase of the waves emitted by the individual elements of the array [4].

The phase of a wave is a measure of how far along its cycle it is. When two waves are in phase, they add together to create a wave with a larger amplitude. When two waves are out of phase, they cancel each other out.

In a linear array, the phase of the waves emitted by the individual elements can be changed by delaying the signal that is sent to each element. The amount of delay that is applied to each element is determined by the angle of the desired beam.

3.6. Smart antennas

3.6.1. Smart antenna

The term smart antenna refers to a system that employs an antenna array and dynamically adjusts the antenna pattern as needed [16]. Smart antenna systems are digital wireless communication antenna systems that transmit and receive multiple radio frequencies by manipulating individual antenna elements as an array with a uniquely specified geometrical configuration. The system also includes a digital signal processing algorithm that is used as the "brain" of the antenna system. This algorithm is used to identify the spatial signal signatures, such as the direction of arrival (DOA) of the required signal/target. The algorithm then uses this information to locate and track the signal using beamforming vectors.

Smart antenna systems have several advantages including:

- ✓ Increased gain and directivity
- ✓ Reduced sidelobes
- ✓ Improved beam steering
- ✓ Increased frequency reuse
- ✓ Improved noise immunity
- ✓ Reduced interference
- ✓ Improved coverage

Smart antenna systems are used in a wide variety of applications including:

- ✓ Radar
- ✓ Acoustic signal processing
- ✓ Wireless cellular communication systems
- ✓ Satellite communications
- ✓ Military communications
- ✓ Medical imaging
- ✓ Radio astronomy

The design and analysis of smart antennas take into consideration a variety of design rules, parameters, and disciplines. During the design of smart antennas, one must be aware of, handle, and have sufficient knowledge of random processing, electromagnetic wave manipulation, wave propagation, spectral estimation methods, more specifically direction of arrival of signals, digital signal processing concerned with adaptive techniques, and individual antenna characteristics [16]. The knowledge of the individual antenna element theory and fundamental characteristics has a critical influence on the overall smart antenna design and requirements. Smart antenna can be classified into two broad categories. These are:

- ✓ Phased Array Antennas (PAA)
- ✓ Adaptive Array Antennas (AAA)

3.6.1.1. Phased Array Antennas (PAA)

Phased array antennas (PAAs) are a type of smart antenna system that uses a combined network of individual radiating antenna elements as an array. The signals coming from or induced by the individual elements are combined to form a single output of the overall array. This process is called beamforming.

The PAA provides maximum gain in the direction of the desired target or signal of interest, which is normally called the beam-pointing direction. The pointing direction can be controlled by adjusting the phase differences among the various individual radiating antennas. This enables their signals to be added in phase in the desired direction, resulting in an array gain equal to the sum of the individual radiating antenna elements' gain [1].

3.6.1.2. Adaptive Array Antennas (AAA)

Unlike phased array antenna systems, in which the required amount of weighting on the individual antenna elements is fixed during the design process, adaptive antenna systems adjust the weights of each radiating element during signal processing. The system controls the adaptive processor to allow the multi-element array pattern to adapt to the current environmental situation.

If we consider a non-stationary target/signal of no interest that is operating at the same frequency as the target/signal of interest, and when a criterion is set to get a maximized signal-to-noise ratio (SNR) as a performance measure, a designer must cancel the interference coming from the moving undesired target dynamically. In other words, the antenna radiation pattern needs to adjust itself intelligently so that the effect of the signal coming from the moving undesired target remains unchanged in the previous null position.

This type of intelligent adjustment of weights on the individual radiating elements to achieve a pattern with optimal performance is accomplished by a system built of adaptive array antennas with internal devices made up of modern digital signal processors [17].

3.7. Introduction to genetic algorithm (GA)

Many research studies have been conducted to develop optimization tools that can efficiently search for possible optimum solutions. Genetic algorithms (GAs) are one such tool. The Genetic Algorithm [18] is an iterative stochastic optimizer that is motivated by Darwin's concept of survival of the fittest and uses methods based on the principles of natural genetics and natural selection to construct search and optimization procedures that best satisfy a predefined goal. The GA modifies a population of individual solutions regularly. The GA selects individuals at random from the current population to be parents and uses them to produce children for the next generation at each step. Over successive generations, the population 'evolves' toward an optimal solution. At each step of the iteration, the GA uses the selection, crossover, and mutation rules to create the next generation from the current population.

The goal of this genetic algorithm is to find a set of parameters that minimize the output of a function. Genetic algorithms differ from most optimization methods because they have the following characteristics [19].

- ✓ They work with a coding of the parameters, not the parameters themselves.
- ✓ They search from multiple points rather than a single point.
- ✓ They don't use derivatives.
- ✓ They use random transition rules, not deterministic rules.

The basic steps involve steps like who among the population is allowed to reproduce and which members of a generation are discarded.

Analytical methods cannot be used to design a thinned array due to the complexity of the synthesis problem. As a result, global optimization tools are a good solution to these issues. Among the different global optimization methods such as genetic algorithms, particle swarm optimization (PSO) [20], simulated annealing (SA) [21], etc. have already been utilized in array antenna synthesis for various applications.

GA can be applied to solve various optimization problems that cannot be solved using standard optimization algorithms, including discontinuous objective function, non-differentiable, stochastic, or highly nonlinear [22].

GA is simple to grasp, and the computer code is simple to write. GA is effective and efficient in the following situations:

- ✓ Search space is large, complex, and poorly understood.

- ✓ Rare domain knowledge or difficult expert knowledge to encode in order to narrow the search space
- ✓ Unavailable mathematical analysis
- ✓ Failure of traditional search methods.

The GA evolutionary process begins with the random generation of individual populations. In each generation, multiple individuals are selected randomly based on the specified fitness function, bred using crossover, and modified using mutation to form a new individual population. Hence, a genetic algorithm involves three main sets of rules or operations to create the next generation from the current population [23]. Majorly, three basic rules govern the formation of the next generation:

- ✓ Selection rules determine the next generation by picking the contributing individuals (parents).
- ✓ Crossover rules create the offspring belonging to the succeeding generation by merging the two parents.
- ✓ Mutation rules impose randomly decided changes to individual parents to form offspring.

GA differs from traditional derivative-based algorithms in two ways:

1. In each repetition, GA generates a population of points. The best point in the population approaches the optimum solution, whereas, classical algorithms generate a single point at each iteration and the sequence of points approaches the optimum solution.
2. GA selects the next population by randomly generating numbers, while classical algorithms select the next point in the sequence by deterministic computation.

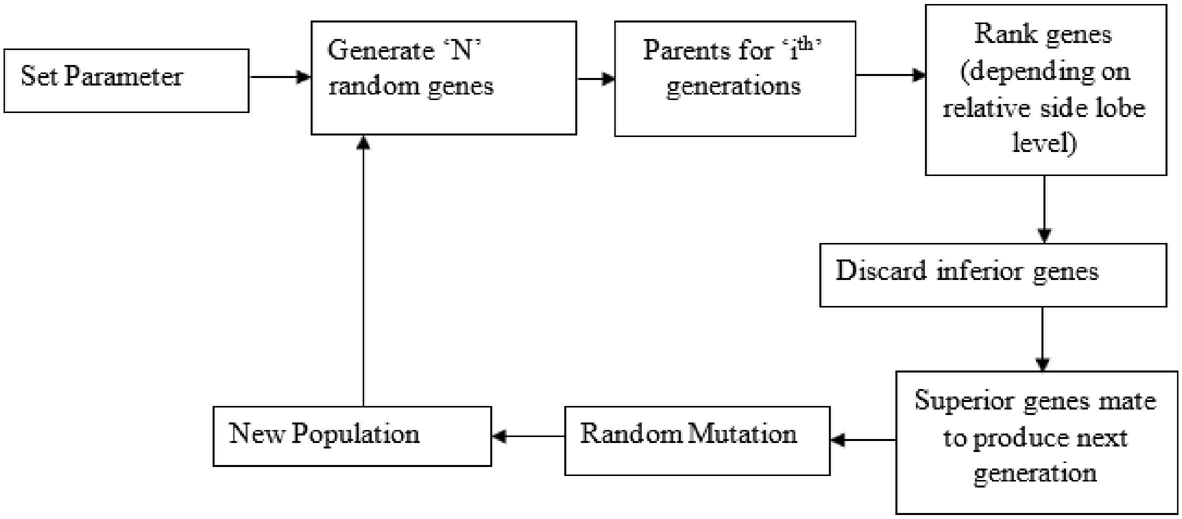

Figure 3.4: Flow Chart of Genetic Algorithm

3.7.1. Generalized Flow Chart of GA

The operation sequence of GA can be described by a simplified flow chart as shown in Figure 3.5 [24].

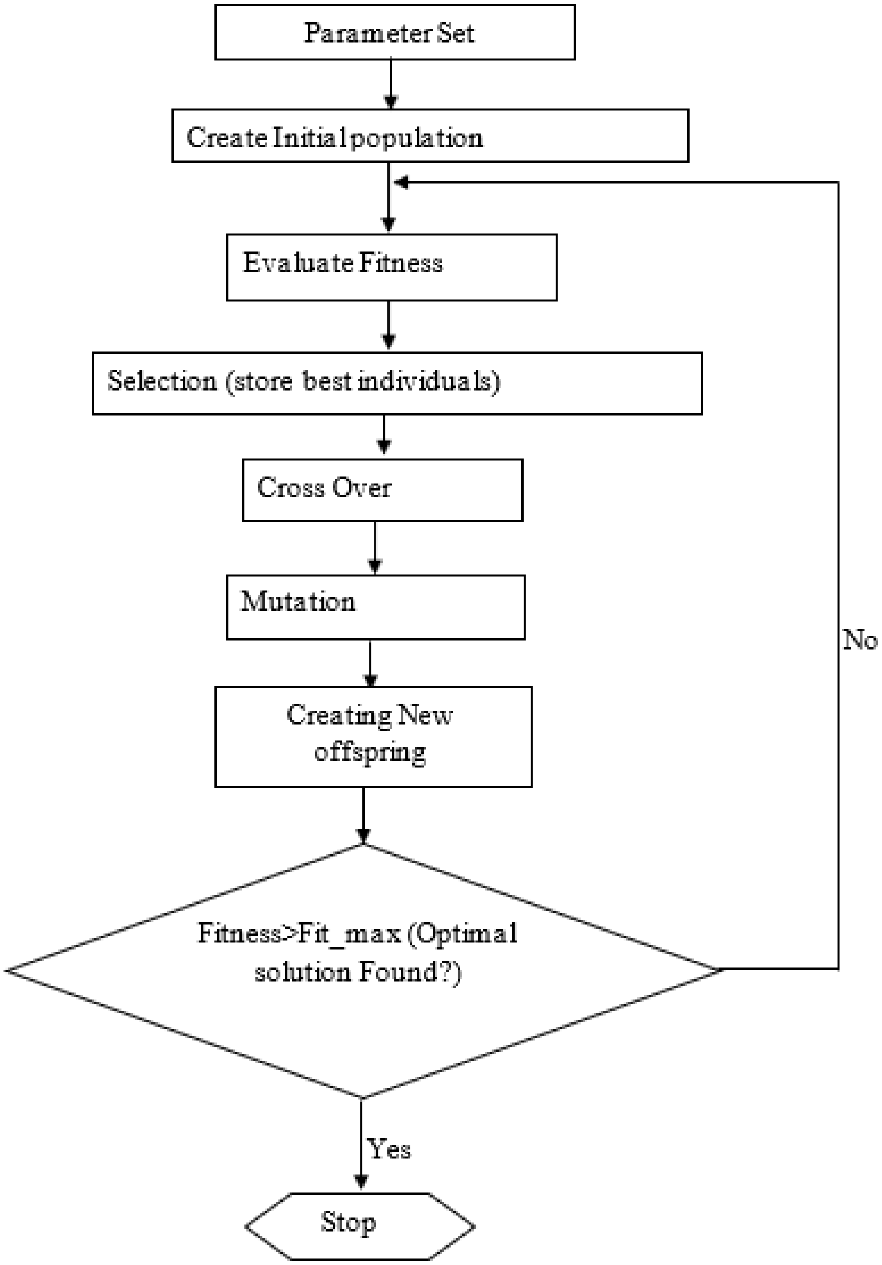

Figure 3.5: Generalized Flow Chart of GA

GA generated the first generation at random and calculated each individual's fitness value based on the fitness function. The fitness criterion suggested the benefits and drawbacks of each individual. The fittest individual has the greatest fitness value. Only the best will survive for the following generation., and the worst will be immediately eliminated. The rest are chosen to produce new generations through recombination. Crossover and mutation are two genetic operators involved in recombination. And it will be recycled for a certain number of generations in order to achieve the best solution (that is the cycle is repeated multiple times until a condition for termination is met).

3.7.2. Genetic Algorithms Parameters

The optimization tool parameter settings have a significant impact on GA search performance. These parameters govern GA's run time, population, and reproduction. The main parameters include; population size, mutation rate, and recombination type [23, 24].

3.7.2.1. Population Size

Population size determines the number of individuals per population and is the most prominent parameter to control the performance of GA. An increased number of populations can increase the number of individual variations in the initial population and increase the amount of fitness evaluation. The population size is related to the number of chromosomes and depends on required applications.

3.7.2.2. Crossover Rate

The crossover rate determines the probability that crossover will take place to generate new individuals in the population by combining part of existing individuals. Though it is suggested to be 0.6 to 0.95, the crossover rate is usually high and depends on the specified application.

Mutation Rate Mutation rate determines the probability that mutation takes place to provide new chromosome information and to prevent premature convergence and saturation of populations with the same chromosomes. Like population size and crossover rate, mutation rate depends on applications. A mutation rate between 0.001 & 0.1 is used for most applications. For all simulation cases, the iterations of the GA optimization tool are terminated with pre-set stopping criteria. The population size is 200, the crossover rate is set to be 0.6 and that of mutation rate is 0.01. In addition to these criteria, the iteration will terminate when the level of all side lobes other than the first side lobe is lower or equal to the first side lobe.

3.8. Thinned Linear Antenna Array Synthesis

There are many published articles [25, 26] dealing with the synthesis of thinned arrays. Element behavior in a thinned array is described in [27]. Some of the other applications of soft computing tools are discussed in [28, 29]. Lee et al. in [30] described optimization of unequally spaced antenna arrays using particle swarm algorithm. Applications of real-coded genetic algorithms for the design of reconfigurable array antennas are discussed in [31, 32]. The latest soft computing tool such as the clonal selection algorithm [33] is successfully used in array antenna synthesis for different applications.

Thinning an array means turning off some elements in a uniformly spaced or periodic array to produce a pattern with a low sidelobe level. In this thesis, the positions of the elements are fixed and all the elements have two states either “on” or “off”, depending on whether the element is connected to the feed network or not. The element is passively terminated to a matched load in the "off" state. If there is no coupling between the elements, removing them from the array is equivalent. Thinning an array [12, 26] to produce low sidelobes is much simpler than unequally spacing the elements for generating patterns with low sidelobe levels. There are an infinite number of ways to arrange the elements nonuniformly.

3.8.1. Linear Antenna Array Modeling

The main advantage of antenna arrays over single antenna elements is that beams can be tilted in desired directions in an array, as well as desired beam shaping, in addition to higher antenna system gain. In mobile communication applications, adaptive antennas (also known as "smart antennas") can direct their main lobe (with increased gain) in a desired direction (e.g., a mobile user in a cellular communication system) and nulls in the direction of interference or jammers. This chapter provides an overview of linear arrays, planar arrays, and smart antennas.

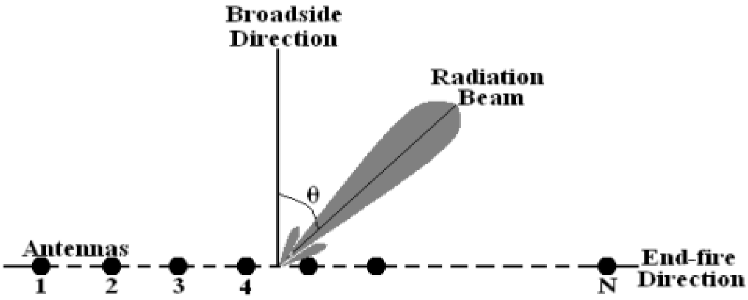

Figure 3.6: Geometry of linear array

The array factor for N element linear array, as shown in Figure 3.6, is given by [1].

$$AF = 1 + e^{j(\frac{2\pi}{\lambda}d*sin\theta+\alpha)} + e^{j2(\frac{2\pi}{\lambda}d*sin\theta+\alpha))} + \cdots + e^{j(N-1)\frac{2\pi}{\lambda}d*sin\theta+\alpha)} \qquad (3.\,15)$$

(3.15) can be written as

$$AF = \sum_{n=1}^{N} A_n e^{j(n-1)(\frac{2\pi}{\lambda}d*sin\theta+\alpha)} \qquad (3.16)$$

$$AF = \sum_{n=1}^{N} A_n e^{j(n-1)\psi} \qquad (3.17)$$

$$where\ \psi = \left(\frac{2\pi}{\lambda}d * sin\theta\right) + \alpha = kdsin\theta + \alpha \qquad (3.18)$$

In (3.16), the angle θ is counted from broadside direction. If this angle is counted from end-fire direction of the array, (3.16) becomes [1].

$$AF = \sum_{n=1}^{N} A_n e^{j(n-1)(\frac{2\pi}{\lambda}d*cos\theta+\alpha)} \qquad (3.19)$$

And k is the phase factor of the array.

For An = 1

$$(AF)e^{j\psi} = e^{j\psi} + e^{j2\psi} + e^{j3\psi} + \cdots + e^{j(N-1)\psi} + e^{jN\psi} \qquad (3.20)$$

$$(AF)e^{j\psi} = \sum_{n=1}^{N} A_n e^{jn\psi} \qquad (3.21)$$

$$(AF)e^{j\psi} - AF = e^{jN\psi} - 1 \qquad (3.22)$$

$$AF = \frac{e^{jN\psi}-1}{e^{j\psi}-1} \qquad (3.23)$$

$$AF = e^{j(\frac{N-1}{2})\psi}\frac{\sin(N\frac{\psi}{2})}{\sin(\frac{\psi}{2})} \qquad (3.24)$$

Where N shows the number of elements in the array, ‘d’ is the inter-element spacing and $e^{j(\frac{N-1}{2})\psi}$ is the phase factor.

Neglecting the phase factor,

$$AF = \frac{\sin(N\frac{\psi}{2})}{\sin(\frac{\psi}{2})} \qquad (3.25)$$

For small values of ψ, the above equation reduces to

$$AF = \frac{\sin(N\frac{\psi}{2})}{(\frac{\psi}{2})} \qquad (3.26)$$

As the maximum value of (3.25) or (3.26) is equal to unity, the normalized array factor can be written as

$$\mathrm{AF} = \frac{1}{\mathrm{N}}\left[\frac{\sin\left(\mathrm{N}\frac{\psi}{2}\right)}{\sin\left(\frac{\psi}{2}\right)}\right] \qquad (3.27)$$

$$\mathrm{AF} = \frac{\sin\left(\mathrm{N}\frac{\psi}{2}\right)}{\mathrm{N}\frac{\psi}{2}} \qquad (3.28)$$

Nulls can be obtained by making (3.27) or (3.28) equal to zero.

Hence $\sin\left(\mathrm{N}\frac{\psi}{2}\right) = 0$, i.e., $\mathrm{N}\frac{\psi}{2} = \pm n\pi$ for $n = 1,2,3\ldots\ldots\ldots$ and $n \neq N, 2N\ldots\ldots$

Similarly in order to steer the main beam in the end-fire direction that is at $\theta = 0° or\ 180°$, the progressive phase shift should be $\psi = \pm \mathrm{kd}$.

If the beam direction is θ_0 from the broadside direction at wavelength λ, then the progressive phase shift is given as [34].

$$\propto = \frac{-2\pi \mathrm{d}}{\lambda}\sin\theta_0 \qquad (3.29)$$

If angle θ_0 is counted from the end-fire direction,

$$\propto = \frac{-2\pi \mathrm{d}}{\lambda}\cos\theta_0 \qquad (3.30)$$

The normalized array factor is

$$AF = \mathrm{A_{norm}} = \frac{\mathrm{AF}}{\mathrm{AF_{max}}} \qquad (3.31)$$

In (3.30), the maximum value of array factor AF is $\mathrm{AF_{max}}$

3.9. GA Optimization Overview

The Genetic Algorithm [35] is an iterative stochastic optimizer that is motivated by Darwin's concept of survival of the fittest and uses methods based on the principles of natural genetics and natural selection to construct search and optimization procedures that best satisfy a predefined goal. Figure 3.5 depicts the flow chart diagram of GA. A population is a group of individuals or solutions, and an individual is a collection of variables. Selection, crossover, and mutation are the three genetic operators [35]. They are the algorithm's heart. The steps used in this algorithm are summarized as follows:

Step 1: Create a random population of P individuals within the variable constraint range.

Step 2: Evaluate the fitness of the individuals using the fitness function.

Step 3: Select the superior individuals using nonlinear ranking [35] and place them in the mating pool. To accommodate more copies of superior individuals in the new population, the number of individuals in the mating pool is the same as P. Highly fit individuals have more copies in the mating pool, while less fit individuals have fewer copies.

Step 4 Individuals placed in the mating pool are now allowed to mate and then mutate using heuristic crossover and uniform mutation [35]. Two parents' mate to produce two children during the crossover process. Subsequent mutations of the parents increase population diversity and explore new areas of parameter search space. Choose C pairs of parents at random from the mating pool to participate in crossover, resulting in C pairs of offspring, and replace these new C pairs of crossover offspring with the chosen C pairs of parents from the mating pool.

Select M number of parents from the mating pool at random to participate in mutation to produce M number of offspring, and replace the chosen M number of parents from the mating pool with these new M number of mutation offspring. A parent's variable is only changed by mutation.

Step 5: The elitist model is the postprocessor. The worst member of the newly generated population is replaced by the best member of the old population. It is used to ensure that the algorithm converges. This step was added to prevent the best-discovered individuals from being lost by chance due to crossover and mutation. It will always keep the best people from one generation to the next.

Step 6: Repeat steps 2–5 until a stopping criterion, such as discovering a sufficiently good solution or completing a maximum number of generations, is met. The final answer is determined by the individual with the highest score in the population.

3.10. Smart Antenna

The need for smart antenna (SA) arises due to some unique challenges in wireless communication systems like limited capacity due to limited allocated spectrum, signal fading and spreading in time, space, and frequency due to radio propagation environment and mobility of users and power constraints due to limited battery life of the mobile device. SA is an antenna array that by using a digital signal processing module generates a beam in a particular direction and eliminates interference. SA reduces cochannel interference and multipath fading, hence providing a higher data rate. Other advantages of smart antenna include improved angle of arrival and direction finding, instantaneous tracking of moving sources, and higher permissible signal bandwidth.

A smart antenna system can adapt the directionality of its radiation pattern to the signal environment automatically. Smart antennas are antenna arrays that use smart signal processing algorithms to identify spatial signal signatures such as the signal's direction of arrival (DOA) and use it to calculate beamforming vectors, which are used to track and locate the antenna beam on mobile targets. Because smart antennas produce radiation beams along the signal's direction of arrival (DOA), significant power savings are possible [36]. Acoustic signal processing, track and scan RADAR, radio astronomy and radio telescopes, and, most notably, cellular systems use smart antenna techniques. SAs can be categorized into two types, viz., switched beam type and adaptive type. These two categories are further subdivided on the basis of single-user and multi-user environments. The switched beam antenna is further subdivided into single beam and multi-beam directional antennas. Similarly, the adaptive antenna array is subdivided into single user and multi user beamforming antennas. Several fixed beam patterns are pre-assigned in switched beam SA and most appropriate beam is used for desired communication. Whereas beam can be steered in any direction according to the estimated signal direction in adaptive type SA and simultaneously null can be produced in the direction of the interferer.

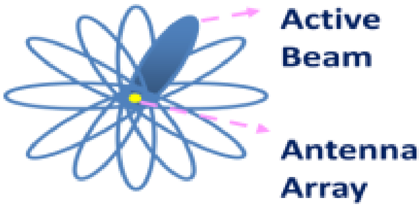

Figure 3.7: Switched beam antenna

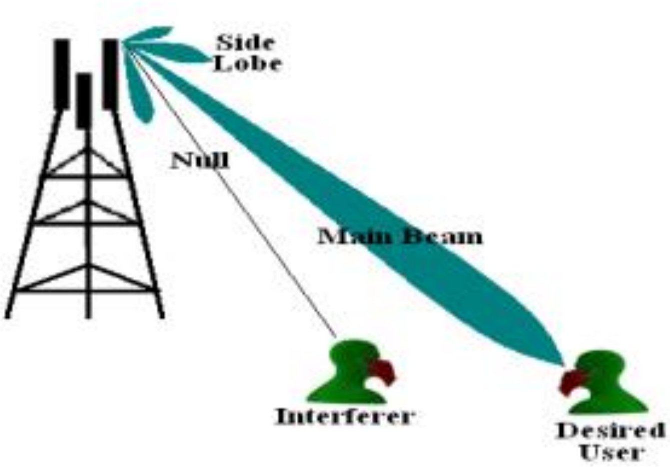

Figure 3.8: Adaptive antenna

The digital beam former in adaptive smart antenna is shown in Figure 3.9. Signals are processed according to the desired performance in mobile network.

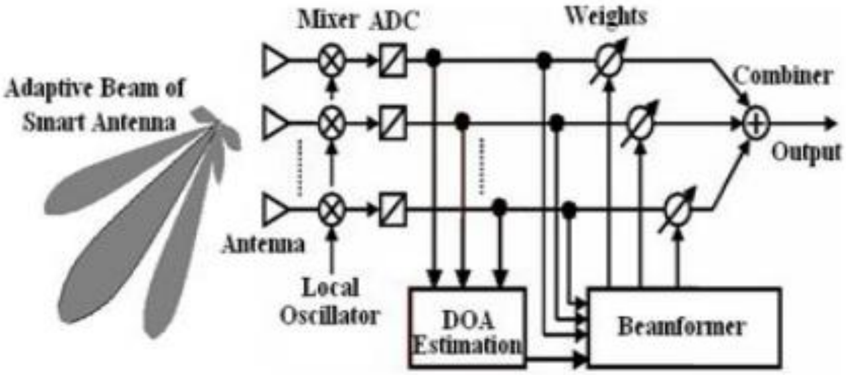

Figure 3.9: Digital beamforming network of smart antenna

The signals are received at the individual antenna elements. The signals are down-converted to baseband or intermediate frequencies and then sent to the analog-to-digital converters (ADCs) which convert them into digital format since the antenna uses digital signal processing (DSP) algorithms to weigh the incoming signal. Then the signals are multiplied with complex weights and weights are summed up adaptively. SA estimates the DOA and DOI of incoming signals. Then beamforming algorithm generates a beam toward the desired direction and a null toward the undesired direction.

Chapter Four

Simulation Results and Discussions

This chapter presents simulation results for different types of linear antenna arrays, namely Uniformly Spaced, Non-Uniformly Spaced, and Non-Uniformly Spaced with Rotated Elements Arrays with N=20, using MATLAB to determine radiation patterns. The chapter shows plots of the side lobe level (SLL) variation against tilt angle for both the original and optimized thinned arrays, as well as the HPBW variation against tilt angle for the original array and the optimized thinned array using a genetic algorithm. These results demonstrate the effectiveness of the genetic algorithm in optimizing the thinned array and significantly improving its HPBW performance. Additionally, the chapter includes the comparison of desired and synthesized antenna patterns, as well as antenna thinning using a genetic algorithm.

Here below is the result for the Radiation Pattern for Uniformly Spaced, Non-Uniformly Spaced, and Non-Uniformly Spaced with Rotated Elements Array for N=20.

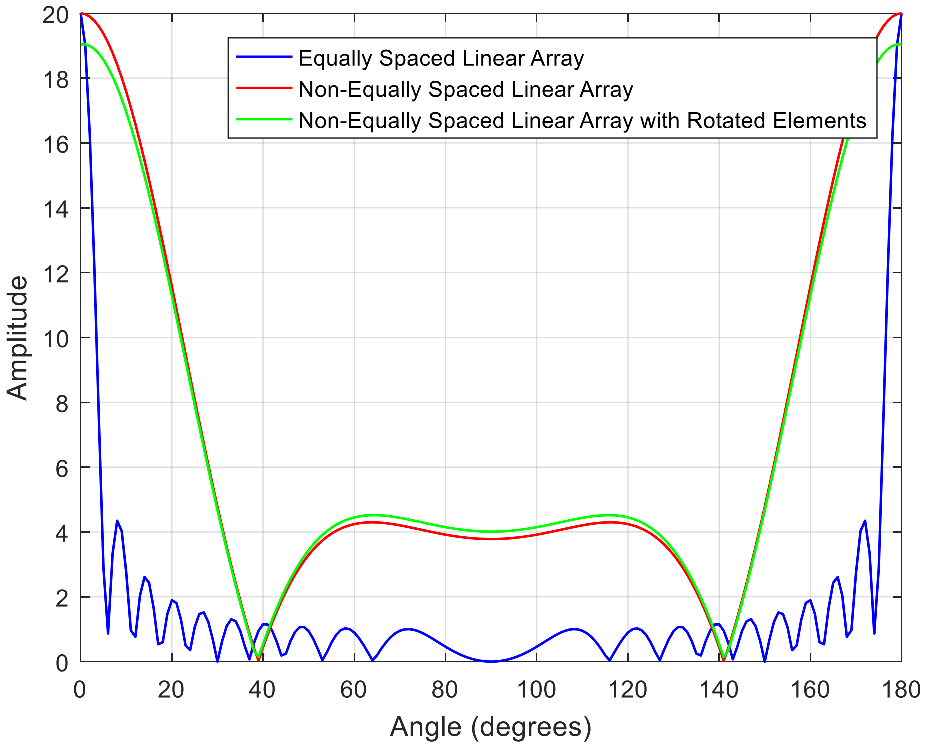

Figure 4.1: Radiation Pattern for Uniformly Spaced, Non-Uniformly Spaced, and Non-Uniformly Spaced with Rotated Elements Array for N=20.

Figure 4.1 above illustrates the radiation patterns of three different linear antenna arrays: an equally spaced linear array (shown in blue), a non-equally spaced linear array (shown in red), and a non-equally spaced linear array with rotated elements (shown in green).

The non-equally spaced linear arrays have higher directivity than the equally spaced linear array due to their elements being positioned at specific locations to enhance their directivity in certain directions. The non-equally spaced linear array with rotated elements also has the added advantage of being able to steer its beam in multiple directions by controlling the phase shifts of its elements. Overall, the graph shows that the radiation patterns of the non-equally spaced arrays are more focused and directive than the equally spaced array. Additionally, the non-equally spaced linear array with rotated elements demonstrates the ability to steer its beam in multiple directions, making it a more versatile option for certain applications.

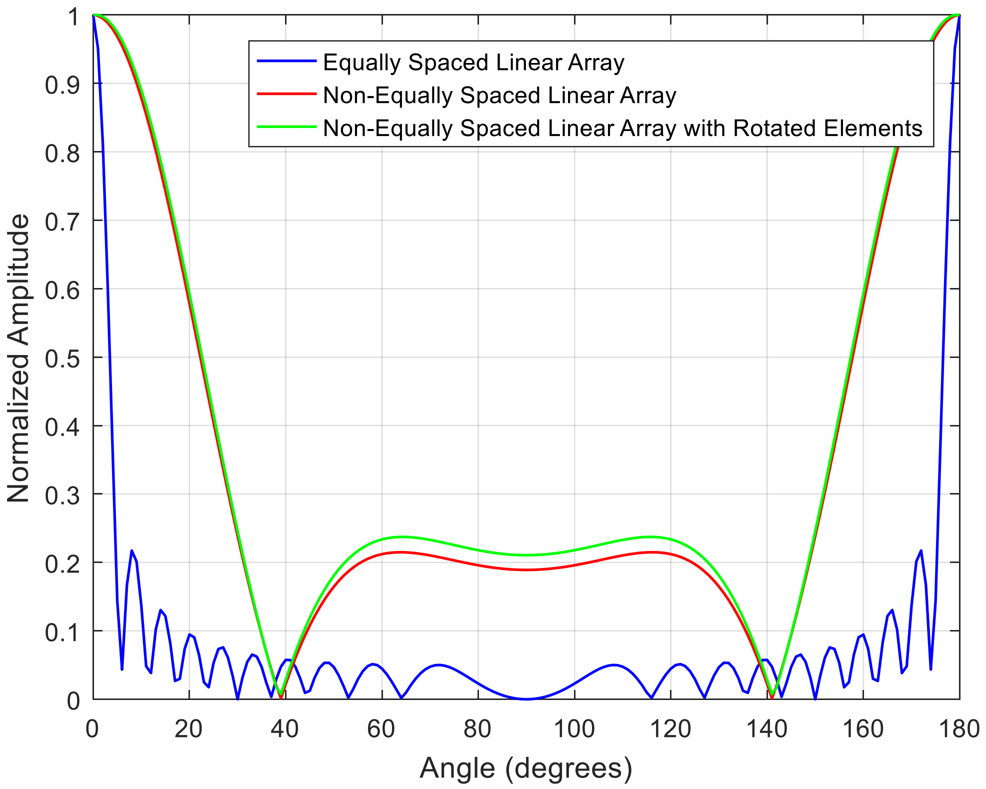

Figure 4.2: Comparison of the normalized amplitude of three different types of linear arrays

Figure 4.2 above shows the normalized amplitude of the three different types of linear arrays for a specific number of antenna elements and spacing between them. The ULA is shown in blue; the NULA is shown in red, and the NU-LAR is shown in green.

Figure 4.3 below depicts a performance comparison of different linear antenna array configurations by varying the spacing (‘d’) and the number of elements (‘N’). Increasing the number of elements generally leads to narrower main lobes and reduced side lobes for all array types, while increasing the spacing between elements results in wider main lobes and higher side lobes. Among the three array types, the non-uniformly spaced linear array with rotated elements (NU-LAR) exhibits the highest directivity and lowest side lobe levels, especially for larger ‘N’ and smaller ‘d’ values. However, achieving beam steering with NU-LAR requires more complex element rotations. The non-uniformly spaced linear array (NULA) generally offers better directivity than the equally spaced linear array (ULA) for all ‘d’ and ‘N’ values, highlighting the advantages of non-uniform spacing. On the other hand, ULA is the simplest and most commonly used linear array, but it tends to have wider main lobes and higher side lobe levels compared to the other two array types.

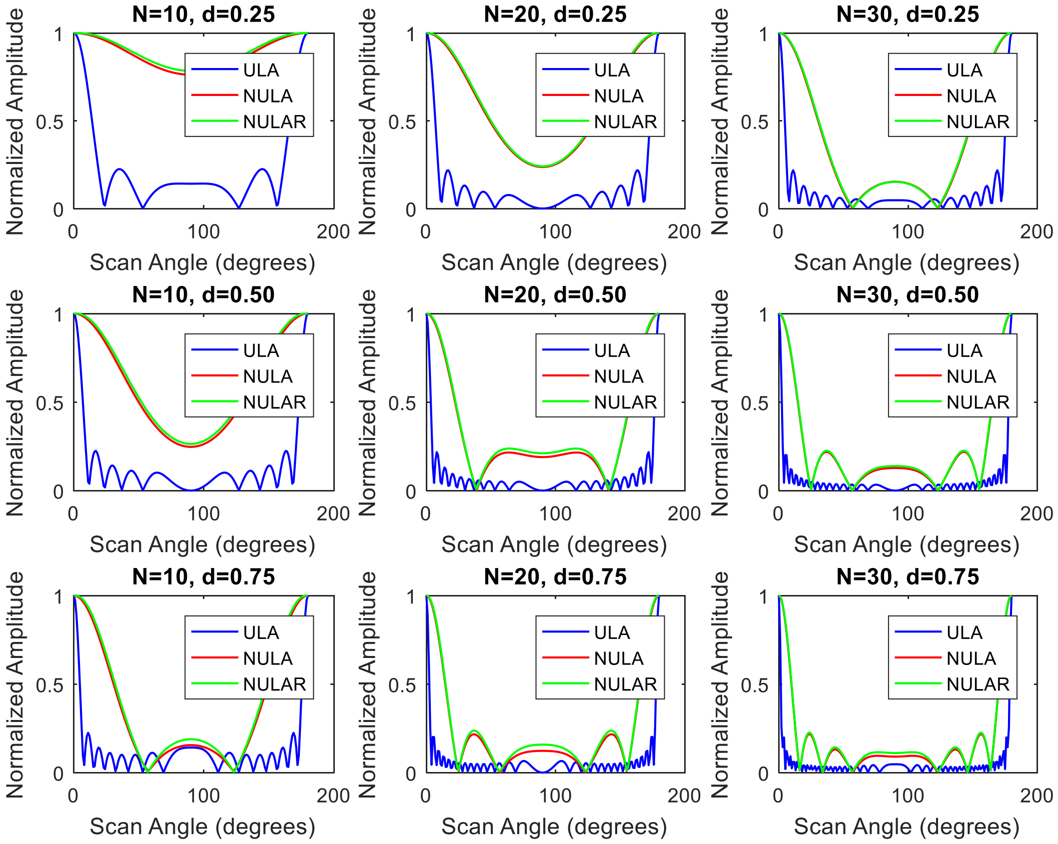

Figure 4.3: Comparison of the normalized amplitude of three different types of linear arrays with varying number of antenna elements and spacing between them.

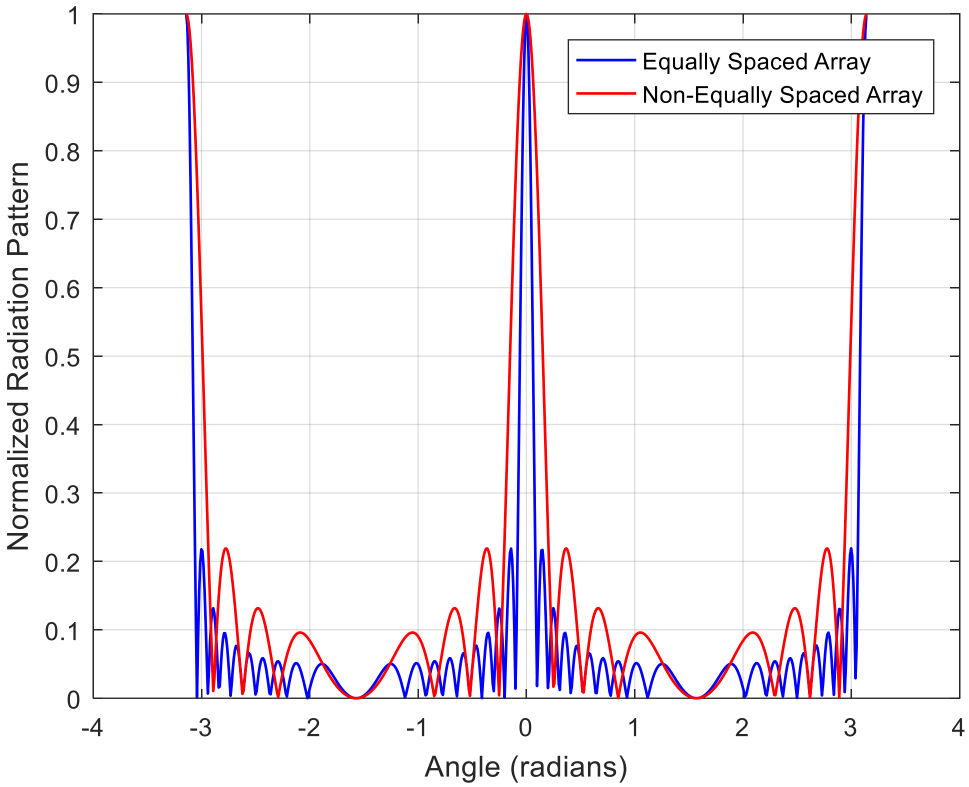

Figure 4.4: Normalized Radiation Patterns of Equally Spaced and Non-Equally Spaced Linear Antenna Arrays

The figure 4.4 above shows a comparison between equally spaced and non-equally spaced linear antenna arrays in terms of beamwidth, directivity, side lobes, and nulls, revealing distinct differences in their radiation patterns.

In terms of beamwidth, the equally spaced array (represented by the blue line) exhibits a narrower beamwidth, indicating a more focused radiation pattern. On the other hand, the non-equally spaced array (represented by the red line) shows a wider beamwidth, suggesting a broader radiation pattern.

Regarding directivity, the equally spaced array demonstrates higher directivity with a prominent main lobe and lower side lobe levels (blue line). In contrast, the non-equally spaced array exhibits lower directivity with a wider main lobe and potentially higher side lobe levels (red line).

When it comes to side lobes, the equally spaced array (blue line) demonstrates lower side lobe levels, implying reduced radiation in undesired directions. However, the non-equally spaced array (red line) have higher side lobe levels, suggesting some radiation away from the main lobe.

Both arrays exhibit nulls, which are regions of low radiation intensity. The equally spaced array (blue line) shows nulls in specific positions, while the non-equally spaced array (red line) may also exhibit nulls, but their position and intensity may differ from the equally spaced array.

Generally, the equally spaced array has a more focused and directive radiation pattern with lower side lobe levels. Conversely, the non-equally spaced array has a broader and potentially more omnidirectional pattern with potentially higher side lobe levels.

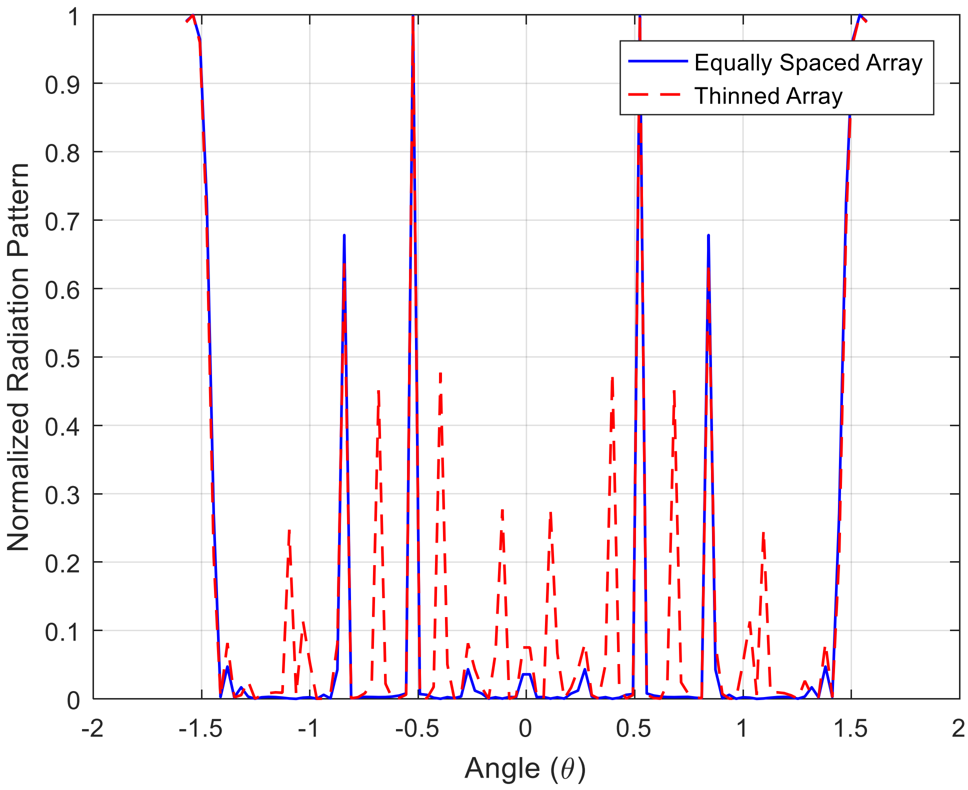

Figure 4.5: Radiation Patterns of Equally Spaced Linear Antenna Array with and without Thinning

The plotted graph shows a comparison between the normalized radiation patterns of an equally spaced linear antenna array and a thinned array. The blue line represents the equally spaced array, while the red dashed line represents the thinned array. By analyzing the shape and characteristics of the radiation patterns, we can observe the impact of thinning on the radiation pattern, including changes to the main lobe and side lobes, beamwidth, directivity, and gain. The thinned array achieves sparsity by reducing the number of elements, but this may result in modifications to the radiation pattern. The comparison between the equally spaced and thinned arrays highlights the trade-off between sparsity and performance.

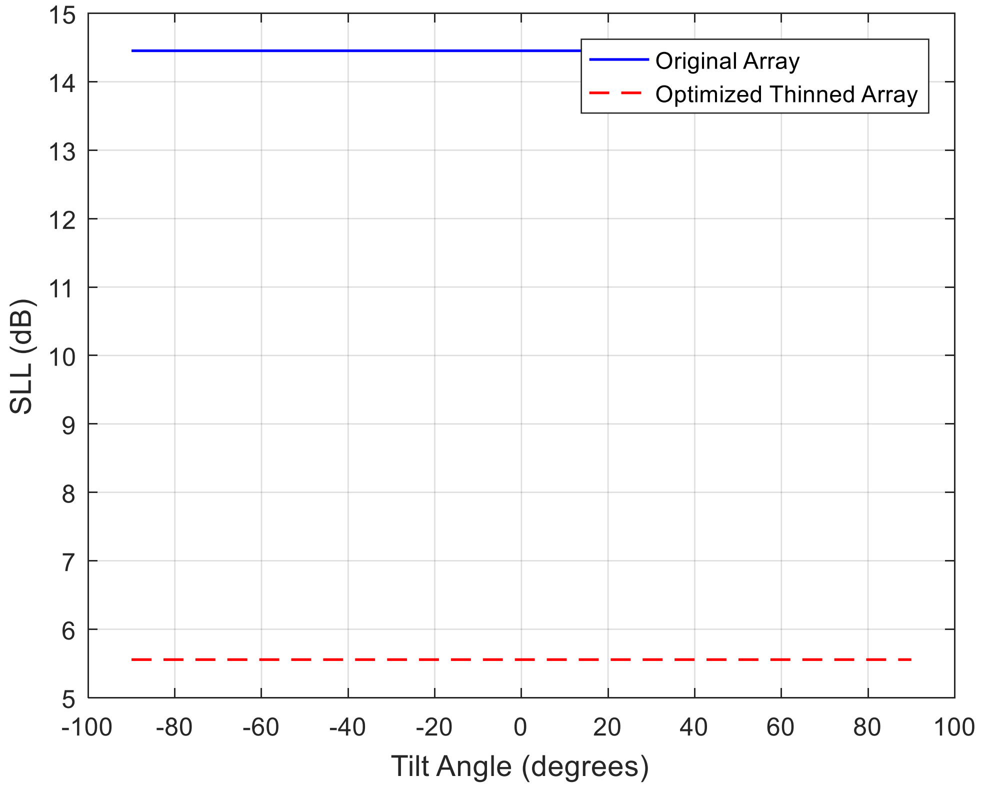

Figure 4.6: Plot of SLL Variation against Tilt Angle for Original and Optimized Thinned Arrays

The figure 4.6 above shows the variation of the SLL (Side Lobe Level) in dB against the tilt angle in degrees for an original array and an optimized thinned array using a genetic algorithm. The blue line represents the SLL of the original array, while the red dashed line represents the SLL of the optimized thinned array.

The figure allows us to observe the impact of thinning on the SLL of the antenna array. By comparing the two patterns, we can see that the optimized thinned array has a lower SLL than the original array for most tilt angles. This indicates that the optimized thinned array has better directivity and reduced side lobes compared to the original array.

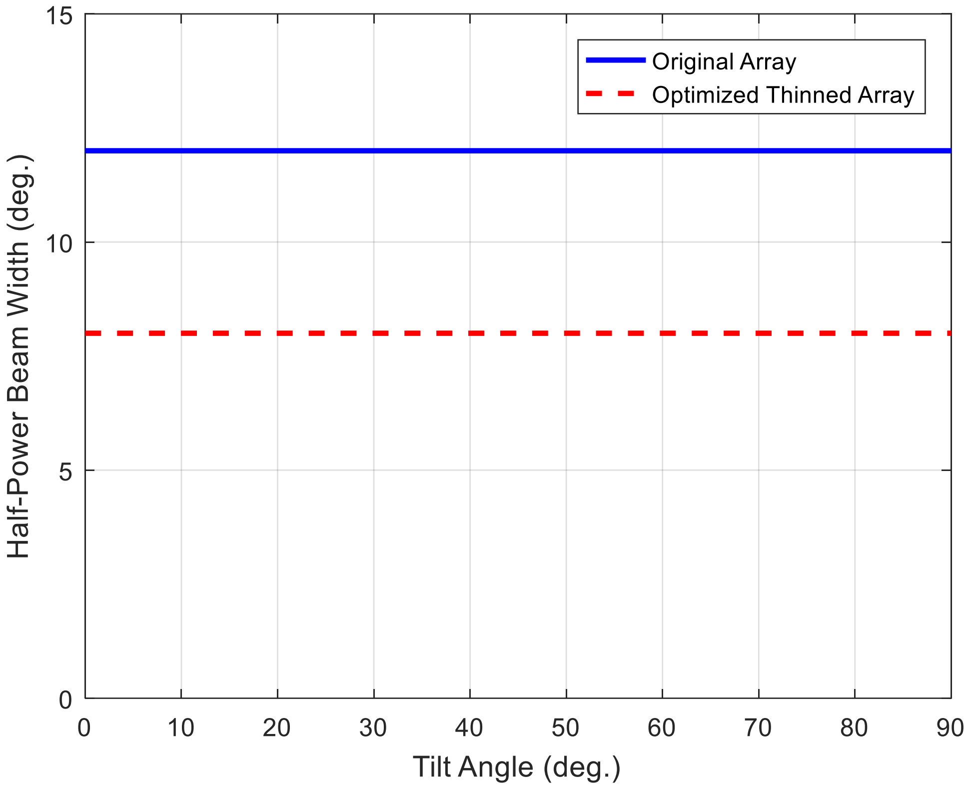

Figure 4.7: A plot of half-power beam width (deg.) variation against tilt angle (deg.) for Original Array and optimized thinned Array using genetic algorithm.

The plot in Figure 4.7 above illustrates the variation of the half-power beam width (HPBW) against the tilt angle for both the Original Array and the optimized thinned Array using a genetic algorithm. The results clearly demonstrate that the optimized thinned Array exhibits a significantly narrower HPBW compared to the Original Array across all tilt angles.

At a tilt angle of 0 degrees, the HPBW of the optimized thinned Array is approximately 8 degrees, while the HPBW of the Original Array is around 12 degrees. This indicates that using a genetic algorithm to optimize the thinned array can greatly improve its performance in terms of beam width. This scenario suggests that by reducing the number of elements in the array while maintaining its overall structure, the genetic algorithm can find an optimal configuration that minimizes the HPBW across all tilt angles. This optimization process enables the array to achieve a more focused and narrower beam, resulting in improved beam directivity and gain.

4.1.Desired and synthesized antenna pattern comparison

Figure 4.8 below compares the desired and synthesized antenna comparison. It is observed that the synthesized array exceeds the beamwidth requirement of the desired antenna pattern. However, the sidelobes are much larger in the synthesized array than the desired antenna pattern. The sidelobes can be reduced by applying a window technique to the array. Thus, it is observed in Figure 4.9 that the sidelobe level of the array is lower compared to the performance in Figure 4.8 after applying windowing operation to the array.

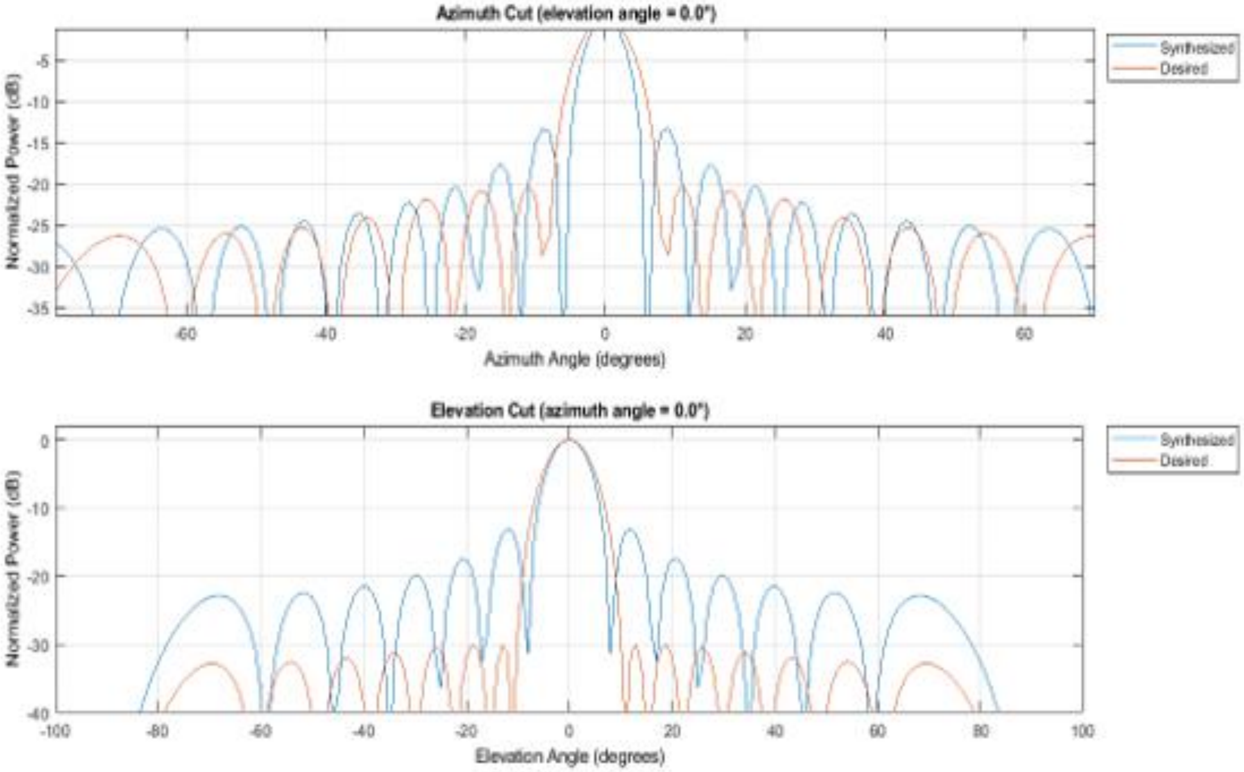

Figure 4.8: Performance comparison of the desired antenna pattern and the synthesized array

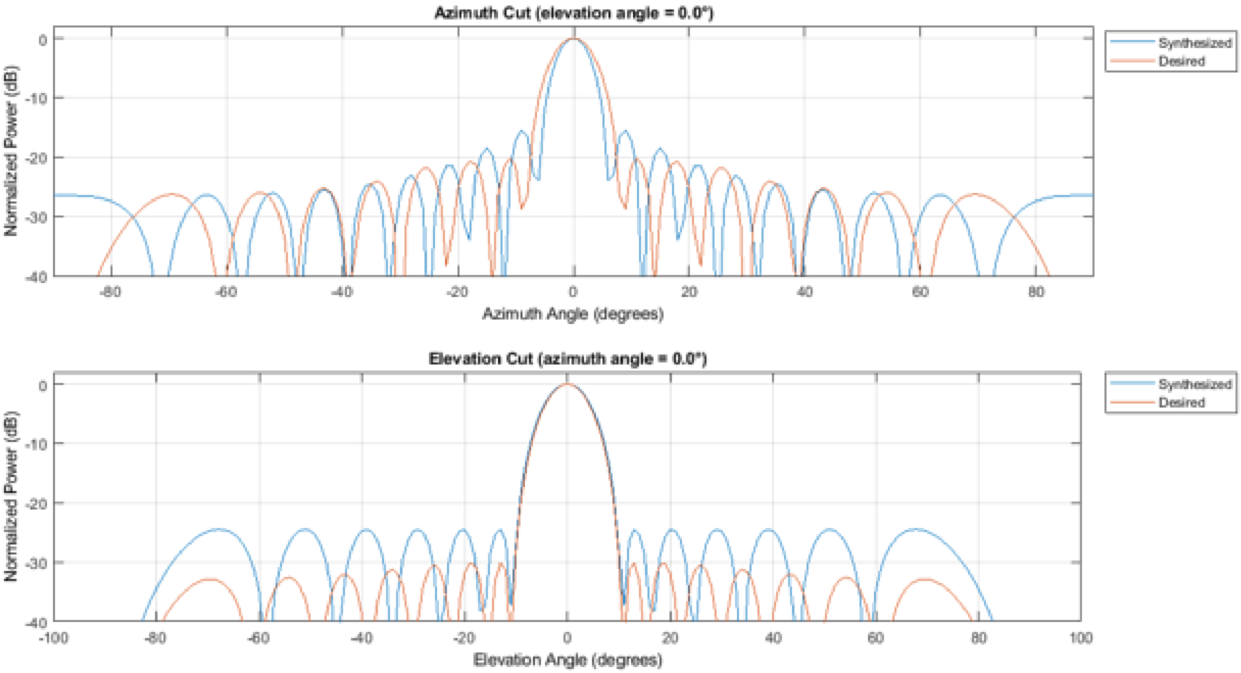

Figure 4.9: Performance comparison of the synthesized array and the desired antenna after applying the windowing operation to the array

Figure 4.10 below depicts the desired 3D pattern, the synthesized 3D pattern, the resulting array geometry, and the taper.

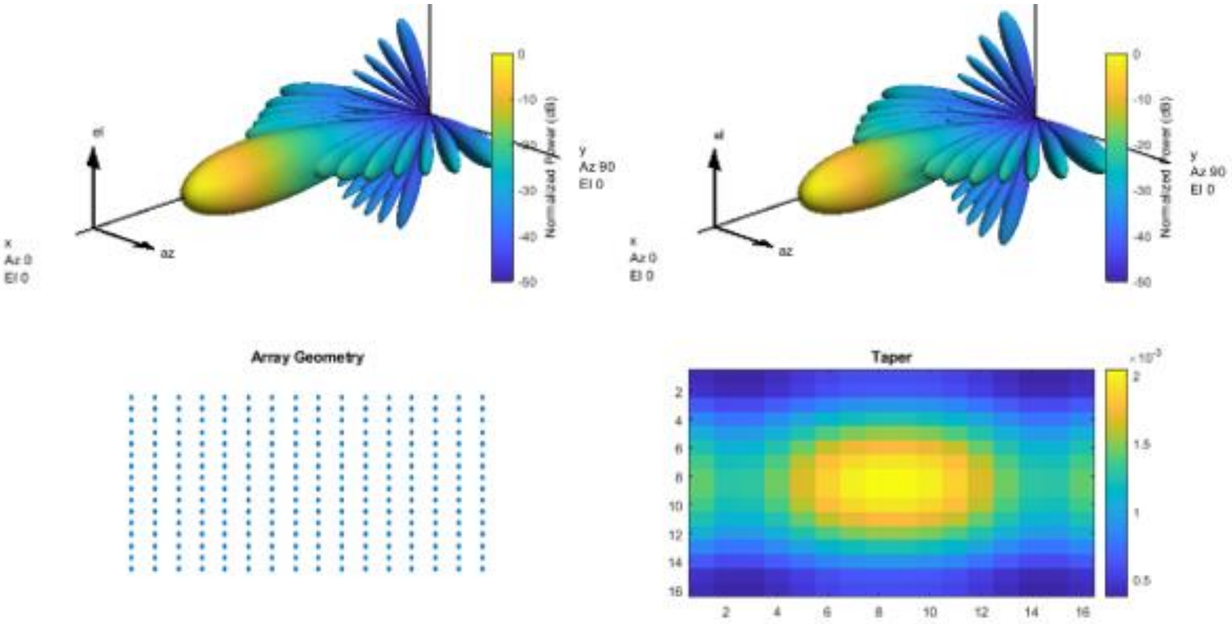

Figure 4.10: Comparing 3D patterns of synthesized and desired antenna

4.2. Antenna thinning using a genetic algorithm

A genetic algorithm achieves the optimal solution by simulating the natural selection process. It starts with randomly selected candidates as the first generation. At each evolution cycle, the algorithm sorts the generation according to a predetermined performance measure (the performance measure would be the ratio of peak-to-sidelobe level) and then discards the ones with lower performance scores. The algorithm then mutates the remaining candidates to generate a newer generation and repeats the process, until it reaches a stop condition, such as the maximum number of generations.

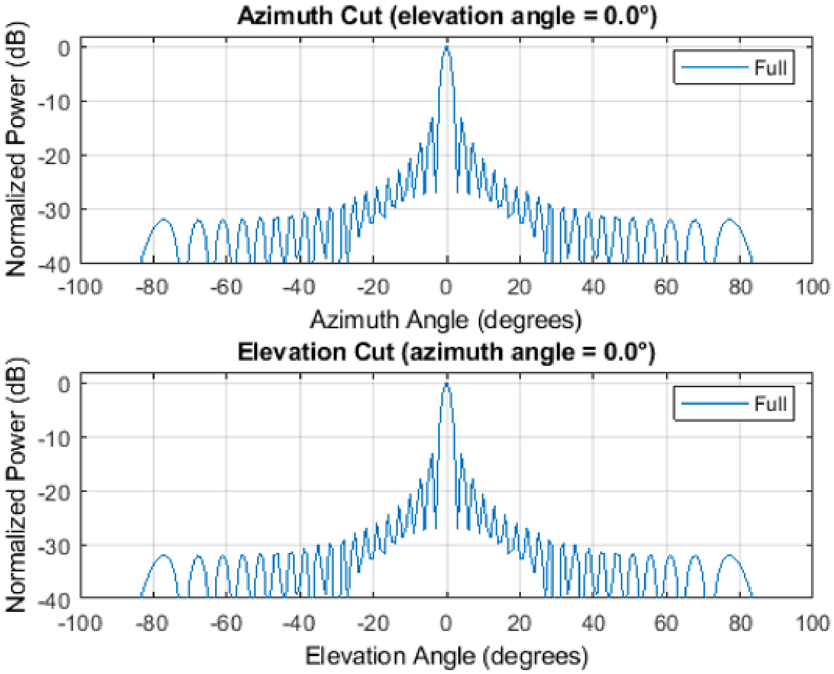

Figure 4.11: Phased array before applying GA

The sidelobe level in Figure 4.11 above before the application of GA is around 13.29 dB. Now we apply the genetic algorithm to see the effect of it on the result. Notice that the URA has symmetry in both rows and columns, thus we can take advantage of this symmetry so that each thinning coefficients candidate applies to only a quarter of the array. This reduces the search space of the algorithm.

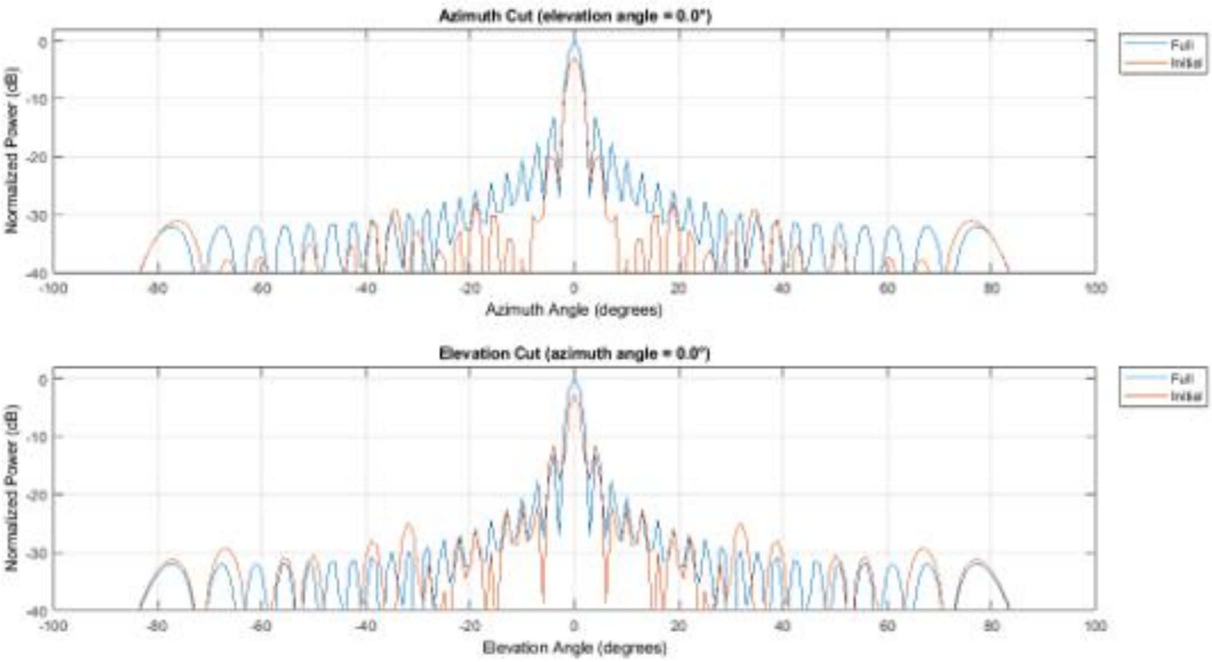

Figure 4.12: Beam pattern after the application of GA with the first-generation candidate

Figure 4.12 above depicts the beam pattern resulting from one typical first-generation candidate. The sidelobe level is lower in the azimuth direction but higher in the elevation direction compared to the full array. The exact sidelobe level and the fill rate of the array is around 8.7 and 71.75% respectively. This means that 71.75% of the array elements are active and the sidelobe level is approximately 9 dB. It needs to be suppressed further. Figure 4.13 below shows the beam pattern resulting from applying a genetic algorithm with 30 generations. Thus, the sidelobe level and the fill rate of the array after applying GA with 30 generations is around 17.38 and 76.5% respectively. It can be seen that the sidelobe level has been further improved to about 17.5 dB with a fill rate of 76.5%. Compared to the first-generation candidate, it uses 5% more active elements while achieving an additional 9 dB sidelobe suppression. Compared to the full array, the resulting thinned array can save the cost of implementing transmitter/receiver (T/R) switches behind dummy elements, which in turn leads to a roughly 25% saving on the consumed power. Also note that even though the thinned array uses fewer elements, the beamwidth is close to what could be achieved with a full array.

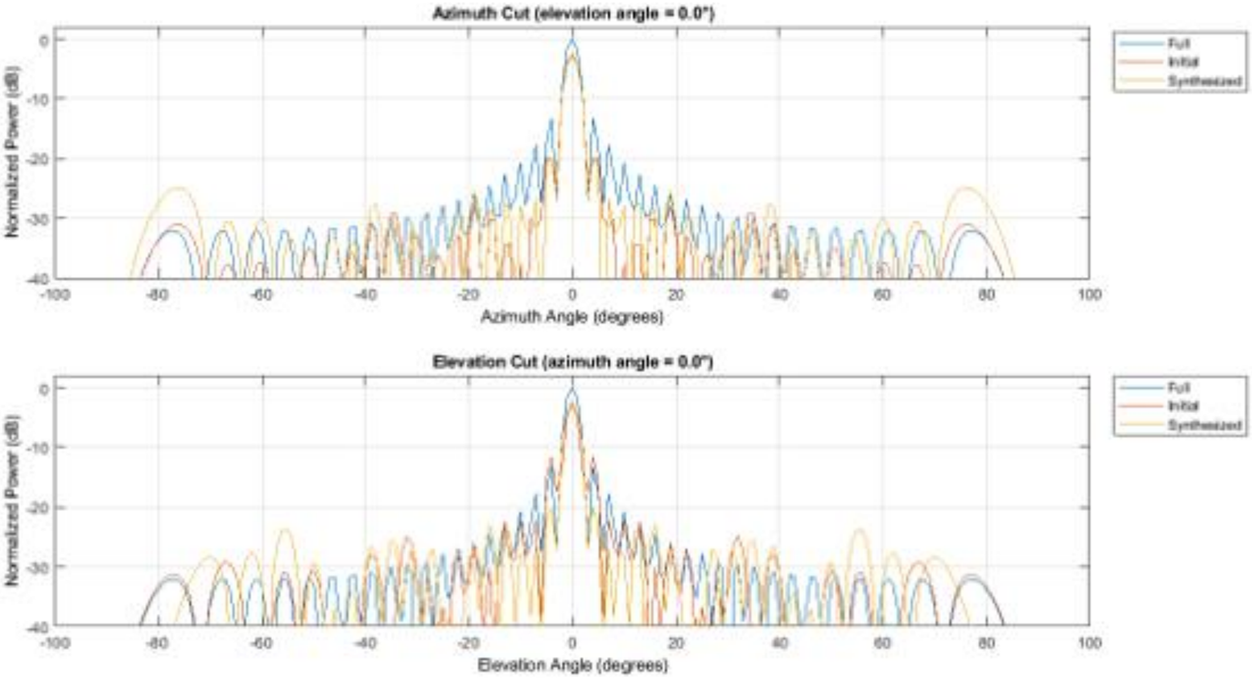

Figure 4.13: Beam pattern resulted from applying genetic algorithm with 30 generations

The final thinned array is shown in Figure 4.14 below with black circles representing the dummy elements.

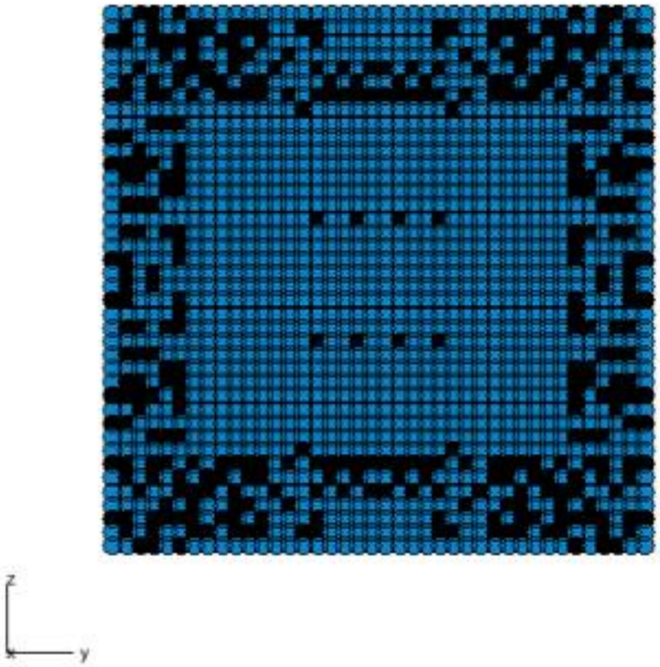

Figure 4.14: Thinned array with specifications (Aperture size: Y-axis = 6m and Z-axis = 6m; Element spacing: Δy = 150mm and Δz = 150mm).

Chapter Five

Conclusion and Recommendations for Future Works

5.1. Conclusion

In this thesis, Reduction methods for side lobe levels (SLL) in linear antenna arrays were studied. Simulation of a linear array of 20 elements with uniform spacing and non-uniform amplitude antenna array was performed using MATLAB. It is known that the side lobe level is the main problem that causes the wastage of energy at the transmitter side. So, reducing the SLL of the antenna array saves radiation power and reduces potential interference in neighboring radiating devices.

In this thesis, a Simulation of the uniform and broadside nonuniform linear arrays with the proposed SLL suppression method of a fixed number of array elements was conducted and results are compared. The proposed array element SLL suppression method together with optimization in inter-element spacing and excitation amplitude shows promising SLL reduction.

From the simulation results obtained in Chapter 4, the following conclusions are made:

- ✓ The study compared radiation patterns of three antenna arrays with N=20: uniformly spaced, non-uniformly spaced, and non-uniformly spaced with rotated elements. Non-uniform spacing and rotated elements significantly improved directivity and reduced side lobes compared to uniformly spaced arrays. Optimizing antenna array design is crucial to achieve improved performance.
- ✓ The study compares the radiation patterns of a linear antenna array with and without thinning. Thinning the array results in a wider main lobe and higher side lobe levels due to a reduction in constructive interference between signals. However, the thinned array also has a wider beam width, which may be desirable in applications requiring broader coverage.
- ✓ The study compared the HPBW of the Original Array and optimized thinned Array using a genetic algorithm. The optimized thinned Array showed a much narrower HPBW compared to the Original Array at all tilt angles, indicating significant performance improvement. The genetic algorithm reduced the number of elements while maintaining the array's structure, resulting in an optimal configuration that minimized the HPBW.

- ✓ Overall, this study demonstrates the effectiveness of genetic algorithms in optimizing antenna Arrays for specific performance criteria.

5.2. Recommendation for Future Work

The only problem examined in this thesis is limited to the comparison of side lobe levels between non-uniform arrays and uniform arrays of the same aperture. This means this thesis is limited to the simulation of uniform and broadside nonuniform linear arrays. In addition to linear arrays,

- ✓ SLL suppression in circularly polarized antenna array by polarization variation of array elements
- ✓ Performance improvement in a planar array of finite length dipole using polarization variation of array elements.
- ✓ Another possibility for future work is the extension of this method for Side lobe power comparisons and directivity comparisons
- ✓ Further research could explore the use of non-uniform amplitude distributions in antenna arrays to further improve their performance.
- ✓ Consider the effect of mutual coupling between antenna elements on the performance of antenna arrays and develop techniques to mitigate its impact.
- ✓ Investigate the use of machine learning algorithms to optimize the design of antenna arrays based on specific performance criteria.

Reference

[1] C. A. Balanis, *Antenna theory: analysis and design*: John wiley & sons, 2016.

[2] D.-G. Fang, *Antenna theory and microstrip antennas*: CRC press, 2017.

[3] D. Devisasi Kala and D. T. Sundari, "A review on optimization of antenna array by evolutionary optimization techniques," *International Journal of Intelligent Unmanned Systems*, vol. 11, pp. 151-165, 2023.

[4] H. Oraizi and M. Fallahpour, "Nonuniformly spaced linear array design for the specified beamwidth/sidelobe level or specified directivity/sidelobe level with coupling consideration," *Progress In Electromagnetics Research M*, vol. 4, pp. 185-209, 2008.

[5] M. Ridwan, M. Abdo, and E. Jorswieck, "Design of non-uniform antenna arrays using genetic algorithm," in *13th International Conference on Advanced Communication Technology (ICACT2011)*, 2011, pp. 422-427.

[6] P. Joshi and R. Dubey, "Optimization of linear antenna array using genetic algorithm for reduction in Side lobs levels and improving directivity based on modulating parameter M," *Optimization*, vol. 1, pp. 1475-1482, 2013.

[7] A. Khalid, S. A. Sheikh, I. U. H. Shah, and Q. U. Khan, "Synthesis of linear antenna array using genetic algorithm to reduce peak sidelobe level," in *2015 9th International Conference on Electrical and Electronics Engineering (ELECO)*, 2015, pp. 346-350.

[8] S. Ogurtsov and S. Koziel, "Sidelobe reduction in linear antenna arrays with corporate-feeds of non-uniform power distribution," in *2017 11th European Conference on Antennas and Propagation (EUCAP)*, 2017, pp. 3259-3263.

[9] S. Bandyopadhyay, A. Chatterjee, and A. Datta, "Genetic Algorithm Driven Linear Antenna Array Sidelobe Level Reduction," in *2021 IEEE Indian Conference on Antennas and Propagation (InCAP)*, 2021, pp. 52-55.

[10] M. Fernández-Delgado, J. Rodríguez-González, R. Iglesias, S. Barro, and F. Ares-Pena, "Fast array thinning using global optimization methods," *Journal of Electromagnetic Waves and Applications*, vol. 24, pp. 2259-2271, 2010.

[11] L. Manica, P. Rocca, and A. Massa, "Design of subarrayed linear and planar array antennas with SLL control based on an excitation matching approach," *IEEE Transactions on Antennas and Propagation*, vol. 57, pp. 1684-1691, 2009.

[12] G. Mahanti, N. N. Pathak, and P. K. Mahanti, "Synthesis of thinned linear antenna arrays with fixed sidelobe level using real-coded genetic algorithm," *Progress In Electromagnetics Research*, vol. 75, pp. 319-328, 2007.

[13] H. J. Visser, "Radiative Wireless Energy Transfer: Rectifying Antennas," in *Compendium on Electromagnetic Analysis: From Electrostatics to Photonics: Fundamentals and Applications for Physicists and Engineers Volume 3 Antennas, Antenna Arrays and Microwave Devices*, ed: World Scientific, 2020, pp. 219-244.

[14] A. Chepala, V. Fusco, U. Naeem, and A. McKernan, "Uniform Linear Antenna Array Beamsteering Based on Phase-Locked Loops," *Electronics*, vol. 12, p. 780, 2023.

[15] H. J. Visser, *Antenna theory and applications*: John Wiley & Sons, 2012.

[16] F. Gross, "Smart antennas for wireless communications with MATLAB," *McGraw Hills*, 2005.

[17] C. Blake, "Phased Array Antennas," in *1971 2nd European Microwave Conference*, 1971, pp. 1-7.

[18] Z. Michalewicz, "Genetic Algorithms+ Data Structures= Evolution Programs. Springer-Verlag, 1999," *Google Scholar Google Scholar Digital Library Digital Library*, 1999.

[19] P. Reed, B. Minsker, and D. E. Goldberg, "Designing a competent simple genetic algorithm for search and optimization," *Water Resources Research*, vol. 36, pp. 3757-3761, 2000.

[20] D. Gies and Y. Rahmat-Samii, "Particle swarm optimization for reconfigurable phase-differentiated array design," *Microwave and optical technology letters*, vol. 38, pp. 168-175, 2003.

[21] J. Rodriguez, F. Ares, and E. Moreno, "Linear array pattern synthesis optimizing array element excitations using the simulated annealing technique," *Microwave and Optical Technology Letters*, vol. 23, pp. 224-226, 1999.

[22] J. Rajashree, "Study on nature based search algorithms for solving optimisation problem with emphasis on application to antennas," 2013.

[23] R. L. Haupt and S. E. Haupt, *Practical genetic algorithms*: John Wiley & Sons, 2004.

[24] D. A. Coley, *An introduction to genetic algorithms for scientists and engineers*: World Scientific Publishing Company, 1999.

[25] O. Quevedo-Teruel and E. Rajo-Iglesias, "Ant colony optimization in thinned array synthesis with minimum sidelobe level," *IEEE Antennas and Wireless Propagation Letters,* vol. 5, pp. 349-352, 2006.

[26] R. L. Haupt, "Thinned arrays using genetic algorithms," *IEEE Transactions on Antennas and Propagation,* vol. 42, pp. 993-999, 1994.

[27] L. Schwartzman, "Element behavior in a thinned array," *IEEE Transactions on Antennas and Propagation,* vol. 15, pp. 571-572, 1967.

[28] S. Banerjee, C. Grosan, A. Abraham, and P. Mahanti, "Intrusion detection on sensor networks using emotional ants," *International Journal of Applied Science and Computations,* vol. 12, pp. 152-173, 2005.

[29] A. Abraham, N. S. Philip, and P. Mahanti, "Soft computing models for weather forecasting," *International Journal of Applied Science and Computations,* vol. 11, pp. 106-117, 2004.

[30] K.-C. Lee and J.-Y. Jhang, "Application of particle swarm algorithm to the optimization of unequally spaced antenna arrays," *Journal of Electromagnetic Waves and Applications,* vol. 20, pp. 2001-2012, 2006.

[31] G. Mahanti, A. Chakraborty, and S. Das, "Design of fully digital controlled reconfigurable array antennas with fixed dynamic range ratio," *Journal of electromagnetic Waves and Applications,* vol. 21, pp. 97-106, 2007.

[32] G. Mahanti, A. Chakraborty, and S. Das, "Phase-only and amplitude-phase only synthesis of dual-beam pattern linear antenna arrays using floating-point genetic algorithms," *Progress In Electromagnetics Research,* vol. 68, pp. 247-259, 2007.

[33] A. Akdagli, K. Guney, and B. Babayigit, "Clonal selection algorithm for design of reconfigurable antenna array with discrete phase shifters," *Journal of Electromagnetic Waves and Applications,* vol. 21, pp. 215-227, 2007.

[34] E. Jordan and K. Balmain, "Electromagnetic Waves and Radiating Systems, Prentice Hall," *Englewood Cliffs, New Jersey,* 1968.

[35] Á. E. Eiben, R. Hinterding, and Z. Michalewicz, "Parameter control in evolutionary algorithms," *IEEE Transactions on evolutionary computation,* vol. 3, pp. 124-141, 1999.

[36] T. K. Sarkar, M. C. Wicks, M. Salazar-Palma, and R. J. Bonneau, *Smart antennas*: John Wiley & Sons, 2005.