ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF ELECTRICAL & COMPUTER ENGINEERING

SIDE LOBE SUPPRESSION IN LINEAR POLARIZED ANTENNA ARRAYS

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A thesis submitted to AAiT School of Electrical and Computer Engineering in Partial Fulfillment of the requirements for the Degree of Masters of Science in Communication Engineering

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Declaration

I the undersigned, declare that the thesis comprises my own work in compliance with internationally accepted practices; I have fully acknowledged from the work and referred all materials used in this thesis work.

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Abstract

Side lobe suppression is one of the most important design considerations of linear antenna array to reduce interference and wastage of radiation power. Side lobe level reduction also avoid indicating false target. The reduction of side lobes can be achieved by proper calibration of inter element spacing, excitation amplitude or both inter element spacing and excitation amplitude at a time. In addition to these commonly used methods of side lobe suppression, changing the orientation of selected elements by rotating them about the normal of the array axis can change the polarization of the element pattern. This technique can produce polarization variation as compared with uniformly oriented elements. The purpose of the rotation of elements is to create interference in the side lobe direction of non-rotated array elements. Due to this created interference, the side lobe level of the whole array can be suppressed. This thesis presented side lobe level suppression of linear antenna arrays employing rotation of array elements. Simulations were performed using MATLAB and genetic algorithm optimization tool has been used to find angle of rotation, inter element spacing and excitation amplitude.

Employing rotation of symmetrically positioned array elements, side lobe levels of -17.15dB for uniformly spaced & uniformly excited linear array, -20.40dB for non-uniformly spaced & uniformly excited linear array, -27.25dB for uniformly spaced & non-uniformly excited linear array and finally -28.02dB for non-uniformly spaced & non-uniformly excited linear arrays have been obtained, as can be seen on result, for a total of 10 array elements. As compared to radiation pattern of uniform linear arrays without rotation of elements, the obtained results show significant reduction of side lobe level. As a result of this side lobe reduction, energy wastage and interference outside of the main beam can be minimized with considerable amount and the performance of the array can be improved.

Key Words: Antenna, Side lobe level, linear array, element spacing, excitation amplitude, uniform spacing, uniform excitation, angle of rotation, polarization, rotation,

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Acronyms

5G	5th Generation
AF	Array Factor
AM	Amplitude Modulation
APSO	Accelerated Particle Swarm Optimization
DE	Deferential Evolution
DRR	Dynamic Range Ratio
EF	Element Factor
FFA	Fire Fly Algorithm
FNBW	First Null Beamwidth
GA	Genetic Algorithm
GPS	Global Positioning System
HF	High Frequency
HPBW	Half Power Beamwidth
IWO	Invasive Weed Optimization
MIMO	Multiple Input Multiple Output
MATLAB	Matrix Laboratory
NUELA	Non-Uniformly Excited Linear Array
NUSLA	Non-Uniformly Spaced Linear Array
PSLL	Peak Side Lobe Level
PSO	Particle Swarm Optimization
RF	Radio Frequency
RFID	Radio Frequency Identification
SLL	Side Lobe Level
UELA	Uniformly Excited Linear Array
UHF	Ultra-High Frequency
ULA	Uniform Linear Array
USLA	Uniformly Spaced Linear Array
VHF	Very High Frequency

Chapter One

Introduction

Recent technological achievements in wireless communication systems created conducive environment to live, work and entertain at a much extent level than ever before. For these successful achievements, wireless communication systems require improvements on network characteristics like, system capacity, network quality and coverage. To enhance these basic requirements, all forms of wireless communication systems have shown a great need for antennas with high resolution, high gain and low side lobe level (SLL). The evolution of wireless communication system and utilization of antenna began since the development of first radio transceiver system in 1886 by Heinrich Rudolf Hertz. Hertz's finding was followed by Marconi's attempt to transmit wireless message over the Atlantic in 1901. The latest advancements of wireless communication systems enabled interconnection of wireless equipment and available technologies into single platform. The most commonly known wireless communication systems applications include satellite communications, sonar communications, GPS navigation systems, radar communications and many others. These wireless communication applications drive the wireless revolution and greatly impact the way of living. Wireless communication utilizes antennas as their main system components to achieve the above-mentioned applications [1].

Standards and requirements of antenna technology are still under research and development, despite its current progress to 5th generation (5G) technology. The 5th generation (5G) technology is expected to bring new standards and protocols without changing the fundamental and everlasting antenna theories. 5G technology requires array antennas with close spacing and utilizes massive multiple-input multiple-output (MIMO) in base station antennas to improve coverage area, throughput, system capacity and reliability requirements [2].

The closeness of array elements spacing provides steerable beam features and small physical space of the overall array. However, closely spaced array elements may introduce undesired mutual coupling effect and undesired side lobes. These undesired features will potentially degrade the array performance [3].

1.1. Motivation of the Research

Now adays most of the day to day activities of the world community is under the influence of wireless communication systems. Wireless communication system enabled us to enjoy modern way of living by facilitating tiresome activities into simple form. In all of the applications wireless communication systems employ single antenna or antenna arrays as one of their building components. Array antennas have ability to produce attractive radiation features as compared to single antenna. However, in addition to good characteristics, antenna arrays also generate undesired side lobes, which highly degrade the quality of the entire system.

1.2. Objective and Scope of the Thesis

1.2.1. General Objective

The general objective of this thesis work is to study a linear polarized antenna array with suppressed SLL to an optimum level by varying orientation of array elements by some arbitrary angles.

1.2.2. Specific Objectives

The specific objectives of this study are limited:

- To analyze the SLL of linear polarized antenna arrays using rotation of array elements
- To study a linear polarized antenna array with suppressed SLL to an optimum level by using Genetic Algorithm optimization tool
- To compare the result with a reference radiation pattern of uniform linear array

1.2.3. Scope of the Study

The scope this study is limited to analyzing and performing simulation of linear polarized antenna arrays using MATLAB software.

1.3. Significance of the Study

Signal transmission power and frequency are very scarce and expensive resources in wireless communication. The presence of interference both on the transmitting and receiving devices is the main limiting factor for system capacity. Transmission power wastage and interference are caused by the presence of high SLLs or inefficiently suppressed side lobes on antennas arrays.

The significance of this study is to suppress the SLL of linear polarized antenna arrays so that the wastage of radiation power and the effect of interference will be considerably reduced.

1.4. Methodology

Though there are different methods to suppress the relative SLL of a linearly polarized antenna array, this work focused on varying the polarization of individual array elements. Polarization variation of array elements can produce interference with neighboring array elements' radiation direction. The produced interference will be added constructively in the radiation direction and destructively in the undesired direction. To accomplish the task different method such as literature review and software setup is described.

1.5. Literature Review

This section is concerned with a revision of previously studied related works on side lobe reduction of linear array antennas. Different researches have been conducted and still going on by different scholars to investigate reasonable ways for antenna array performance improvement. SLL suppression of linearly polarized antenna array was one type of performance improvement. In most previously conducted researches, researchers considered different parameters like spacing between individual array elements, excitation amplitude, excitation phase & array geometry. They used these parameters individually or with combination of some or all of these parameters to improve antenna arrays performance. The spacing between array elements can be designed to be uniform or non-uniform depending on the desire of the researcher, required application and expected outcome. The radiation characteristics of linear antenna array can also be controlled by uniformly or non-uniformly exciting, with or without progressive excitation phase.

Various researcher used different optimization techniques to achieve their desires, including Genetic Algorithm (GA), Particle Swarm Optimization (PSO) [4] [5], Differential Evolution (DE) [6], Invasive Weed Optimization (IWO) [7], Fire Fly Algorithm [8] [9], etc. In this thesis, previous works are reviewed by classifying them into three general categories considering the variation of design variables. The basis for classifications is inter element spacing and excitation amplitude distributions.

First, previous works conducted considering inter element spacing as parameters for Side lobe reduction were reviewed. Secondly, researches that consider excitation amplitude as side lobe suppression parameters were addressed and lastly, researches that jointly consider spacing and excitation were reviewed.

H. Unz, in 1960, [10] studied non-uniformly spaced linear arrays for fixed excitation amplitude to improve array performance. This could probably be the first study on antenna array geometry optimization for performance improvement. A study conducted by two researchers, H. Oraizi and M. Fallahpour, in [11] intended to design a non-uniformly spaced linear array of N elements for fixed First Null Beamwidth (FNBW) and minimum SLL. Beamwidth, SLL and number of array elements were related by graphs. For this study, inter element spacing was designed for specified directivity and minimum achievable SLL and graph showing directivity-SLL relation was derived. To optimize these design requirements, this study employed a combination of Genetic Algorithm and Conjugate Gradient Algorithm. Concept of Neural Network were also used for coupling computation.

Using excitation amplitude as design variable, many studies have been conducted by numerous researchers. A few of them are reviewed in this thesis as presented here. Genetic algorithm has been used in [12] to design non-uniformly excited linear array. In this paper a non-uniformly excited linear array was designed to approximate the beamwidth of uniform linear array. It also produced arrays with smallest SLL than Dolph-Chebyshev and highest directivity than uniform, Binomial & Dolph-Chebyshev. A binary coded Genetic Algorithm has been used to reduce SLL of linear array by excitation tapering for a uniform halfwave length inter element spacing in [13]. Continuous Genetic Algorithm was implemented to find excitation amplitude of linear array that produced reduced SLL in [14]. A new approach was presented in [15] to design and analyze

Chebyshev array without directly applying Chebyshev polynomials to improve directivity and reduce SLL. The author considered equally spaced, unequally excited, broadside back fire antenna arrays. Furthermore, the author used z-oriented odd number of array elements and compared the SLL and beamwidth resulting from uniform, Binomial and Chebyshev excitations. Bernstein's polynomial has been applied in [16] to design the amplitude distributions and control SLL of a uniformly spaced linear antenna array. Pallavi Joshi & Nitin Jain in [17] used genetic algorithm for finding the optimum weights of the antenna array elements. The aim of the research is providing a radiation pattern with reduced sidelobe level and maximum directivity towards the radiation direction. To reduce the peak SLL (PSLL) of a linear array, genetic algorithm was employed as an optimization algorithm in [18] of amplitude distributions of array elements. [19] proposed corporate-feed non-uniform excitation to reduce SLL of uniformly spaced broadside linear array.

In [5], the performance of non-uniform linear antenna array has been analyzed as an independent function of a non-uniform inter element spacing, unequal amplitude excitation and varying number of array size. In this study PSO algorithm is employed to reduce SLL, minimize HPBW, improve directivity and place nulls in a desired direction. A conference paper in [20] proposed non-uniform linear antenna array with unequal excitation amplitude of array elements to reduce SLL and increase directivity without increasing beamwidth. In this study, inter element spacing was designed to increase logarithmically and Bartlett-Hanning windowing function is employed for the excitation amplitude derivation and tested for odd number of array elements. A research journal in [21] used Accelerated PSO (APSO) Algorithm to synthesize linear dipole array with low SLL and the result of dipole radiators is compared with isotropic radiators. APSO is used to optimize the excitation amplitude and inter element spacing of dipole array to produce low SLL for constrained dynamic range ratio (DRR) by taking coupling effect into consideration.

In almost all of the reviewed previous works, only non-uniform inter element spacing, unequal amplitude excitation or both non-uniform spacing and amplitude excitation were used as design optimization variables for SLL suppression of linear array of different types. These side lobe reduction parameters can reduce SLL to desired values expected by the designer. In this work, in addition to the above-mentioned parameters, polarization variation of array elements was employed to further suppress the SLL of linearly polarized broadside linear antenna arrays. This work provided another degree of freedom to shape and control the antenna array radiation characteristics.

1.6. Thesis Organization

The rest chapters of this paper are organized as follows: Chapter 2 contain brief theoretical background of antenna and antenna arrays, Chapter 3 contain problem formulation and analysis, Chapter 4 contain simulation results and discussion and finally Chapter 5 contain conclusion and recommendation for future works.

Chapter Two

Background of Antennas and Arrays

This chapter mainly focused on the description of antennas, types of antennas, antenna arrays and associated performance metrics.

2.1. Background of Antennas

Antennas are made of metallic devices designed for transmission and reception of electromagnetic waves over the air at specified frequency and bandwidth. They are connecting links between free space and electronic devices [1]. Antennas are among the most basic system components of wireless communication. There has been a remarkable increase of antenna design and analysis researches conducted in the past years. Antennas have become indispensable parts of wireless communication systems and electronic devices for the past decades. They are an fundamental parts of modern-day communication devices from hand-held cell phone to the most sophisticated communication systems [1], [22].

Antenna have several applications such as mobile communication, broadcast applications, non-broadcast applications, non-communication applications, etc. Mobile applications involve communications associated with aircraft, spacecraft, ships, or vehicles. Broadcast applications of antennas involve a single transmitter and multiple receivers. On the other hand, non-broadcast applications of antennas include municipal radios, amateur radio, wireless personal communications. Antennas also provide non-communication applications like remote sensing systems and industrial applications [22].

Despite the variation of antennas in type and applications, their operating principle is the same. In addition to being transmitter and receiver devices, antennas act as directional devices due to their ability to optimize electromagnetic radiation in desired direction and suppress in others. [23].

2.2. Types of Antenna

There are different kind of antennas and their application depends on the specified system, their properties and range of operating frequency. The selection of a specific antenna type depends on specified application, environment or economy. Most antennas behave the same both at the transmitting and receiving ends in cases where the systems are constructed from reciprocal components. When the components of a systems are non-reciprocal for example ferrites or amplifiers, reciprocal operation of antenna cannot be possible [24].

Based on their performance characteristics and operating frequency ranges, antennas can generally be categorized into four categories: electrically small antennas, resonant antennas, broadband antennas and aperture antennas [22]

2.2.1. Electrically Small Antennas

Electrically small antennas, sometimes called small antennas, were defined for the first time by Wheeler in 1974 [25]. They are structurally simple and much smaller antennas in their overall size or volume they occupy as compared to transmitted or received signal wavelength. Hence, their performance properties are not sensitive to construction details. In small antennas, $ka \leq 0.5$ where, $k = 2\pi / \lambda$ is the free space wave number and a is the radius of sphere circumscribing the maximum size of the small antenna. The size of small antennas depends on application, however, the largest dimension of small antennas is not greater than the wavelength [26] [27]. Electrical size and physical size are two different quantities. Physically large antennas can be intended to operate at low MHz and below frequency ranges and hence they are electrically small antennas. Physically small antennas are advantageous in terms of their size, weight, cost and mobility [22].

Low directivity, low input resistance, high input reactance, low radiation efficiency, narrow bandwidth and high loss in network match are the general characteristics of electrically small antennas. They are inefficient antenna types due to significant ohmic losses on their structure. They are applicable for mediumwave (AM broadcast) reception in home and vehicle entertainment systems [22]. Developing radio frequency identifications (RFIDs) of size 3cm^2 and operating below 1GHz frequency are also other applications of electrically small antennas. Short dipole (equivalent monopole), small loop, and the dielectrically-loaded patch antennas are the most commonly used small antenna types [28] [29].

2.2.2. Resonant Antennas

Resonant antennas are well known antenna types to meet the requirements of simple structure with attractive input impedance over a single or selected narrow frequency bands. They have broad main beam, low or moderate gain, real input impedance and narrow bandwidth. The common examples of resonant antennas include halfwave dipole, Microstrip patch, Yagi, etc. [22].

i) Halfwave Dipole Antennas

Dipole antenna is an RF antenna made of a simple center-fed wire element and can be designed to operate on high frequency (HF) (in case of amateur radio), very high frequency (VHF) and ultra-high frequency (UHF) ranges of radio frequency spectrum. Though its construction depends on operating frequency and the way in which it will be used, it is made up of two road or wire conductors, oriented on the same axis collinearly to each other with small gap between them as shown in Figure 2.1. The diameter of the roads is very small and the theoretical length of dipole antenna is measured from the end of one road to the other. The length of dipole antenna is of the fundamental parameters to determine its electrical properties such as feed impedance, resonance or non-resonance operating frequency [29].

Dipole antenna is the most vital and commonly used antenna either on its own or part of complicated antenna designs in which it forms main radiating or driven element for another antenna.

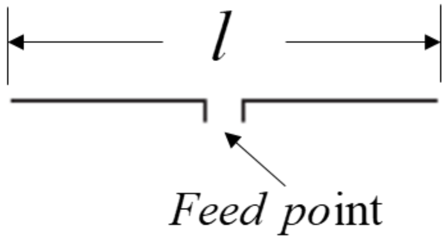


Figure 2.1 - Dipole Antenna [22]

The radio frequency voltage can be fed at any point on the length of the dipole. However, it is commonly applied at the center between the two conductors, where the applied source attains maximum current and minimum voltage. From theoretical point of view, dipole antennas are the simplest and applied antennas.

The direction of currents within the roads of the dipole determines current distribution in the center-fed dipoles. Theoretically, the flow of current is in the same direction and attains its maximum at the center and its nulls at the end of the dipole. Longer dipoles have more current peaks and nulls than short dipoles [1]. Dipole antennas have different forms depending on their size and applications they offer. These dipole antennas include half–wave, folded and short dipole antennas.

Halfwave dipole antenna is type of resonant dipole antenna and most practically applicable wire antenna. The length of half–wave dipole antenna is half of the wavelength of the transmitted or received radio signal.

$$l = \frac{\lambda}{2} \tag{2.1}$$

The wavelength (λ) is mathematically expressed as:

$$\lambda = \frac{c}{f} \tag{2.2}$$

Where, $c \approx 3 \times 10^8 m/s$ is the speed of light in free space and f is the frequency of radiated or received signal [29], [30].

Folded dipole antenna is the most practically applicable wire antenna. It is constructed from two end-to-end connected parallel dipoles that form narrow wire loop, as shown in Figure 2.2. The dimension d is smaller than L and much smaller than wavelength. Dipole antenna is center fed point at one side. Transmission line and modes of antennas are taken into consideration in operational analysis of folded dipoles. [22].

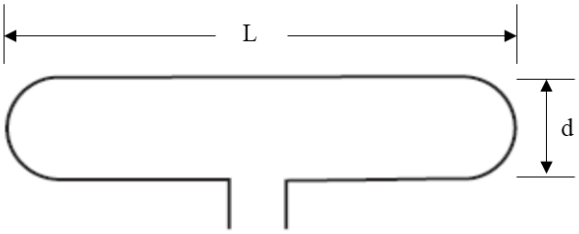


Figure 2. 2 - Folded dipole antenna [23]

ii) Microstrip Patch Antenna

The fist idea to utilize microstrip antennas was proposed in 1953 by Deschamps [28]. Microstrip patch antennas are made of metallic strips (usually copper) mounted on a dielectric substrate supported by a ground plane as shown in Figure 2.3. Microstrip patch antennas are applicable in a wide range of areas due to their ease of design and fabrication. Microstrip patches can poses any shape like square, rectangular, triangular, circular (elliptical), disc sector, ring etc. However, rectangular and circular (elliptic) patches are basic configurations and cover all possibilities in terms of pattern, bandwidth and polarization. They are analytically simple and enable performance predictions [1] [28]. Microstrip antennas are characterized by their advantages and disadvantages.

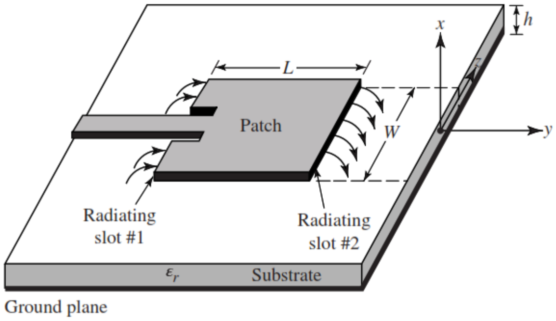


Figure 2.3 – Microstrip antenna [1]

Advantages of Microstrip Patch Antennas

- They are light weight, low volume and low profile.
- They can have any polarization due to the versatility of their geometry printed circuit boards (PCBs).
- They can easily be integrated with Microwave Integrated Circuits (MICs), which are easier to handle and cheapest than the alternative wave guide.
- Their manufacturing cost is low.
- They are conformable to any surface.
- They can be realized in a very compact form, desirable for personal and mobile communication hand held devices.

Disadvantages of Microstrip Patch Antennas

- They have narrow bandwidth
- They have lower power gain
- Their power handling capacity is lower
- They have limitation in frequency
- They have not pure polarization
- They are loss intolerant

iii) Yagi Antenna

Yagi antenna also called Yagi-Uda antenna is practical radiator in HF, VHF and UHF bands. Yagi antenna is made of multiple dipole elements grouped into three main components, namely: resonant dipole driver, director and reflector as given in Figure 2.4. One of the elements directly get energy from the guided medium and the rest elements are parasitic radiators. Parasite elements are energized by induced current through mutual coupling [1] [28]. Yagi antennas are simple and exhibit improved performance as compared with dipole antennas [22].

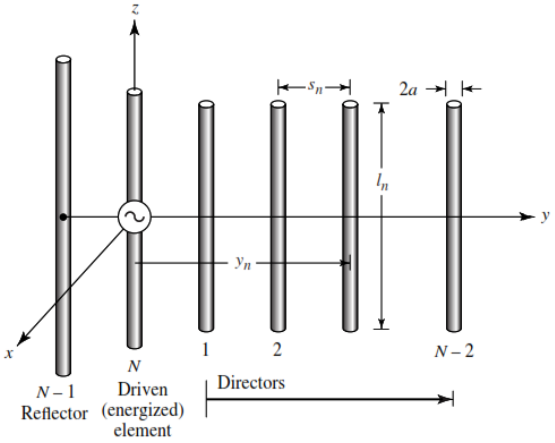


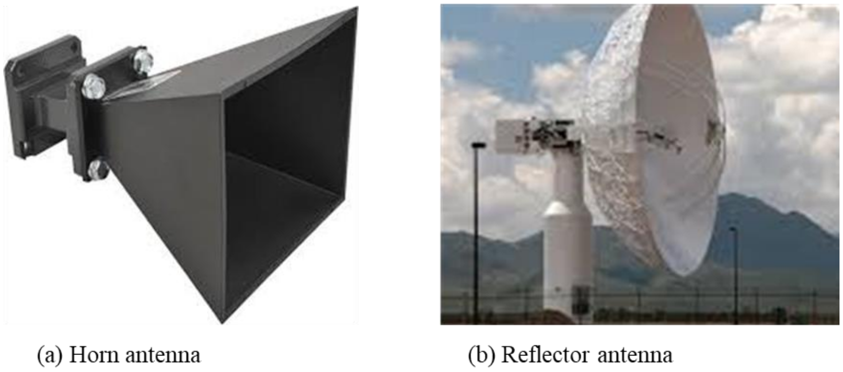
Figure 2.4 - Yagi-Uda Antenna [1]

2.2.3. Broadband Antennas

There are several applications that require antennas operating over wider range of frequency. Antennas fulfilling such operational requirements are broadband antennas. Broadband antennas have been research area for several years. They have interesting performance properties in relation to radiation pattern, gain and impedance over wide range of frequency. Broadband antennas have active region from which most of the power is radiated with linear polarization. The active region is located on linear elements about halfwave length in extent. Since, only the active region of broadband antenna is responsible for radiation at a given frequency, it produces a nearly constant and low gain. Broadband antennas are generally characterized by low or moderate constant gain, real input impedance and wide bandwidth properties. Typical examples of broadband antennas include log-periodic antenna, spiral antenna, and complementary antennas [22] [31].

2.2.4. Aperture Antennas

Aperture antennas are most frequently used in ultra-high (microwave) or above frequency ranges. They are easily mountable on spacecraft or aircraft bodies and hence are applicable antennas for space exploration. They can be characterized by various shapes namely; horn or wave guide with square aperture, rectangular, circular, elliptical, or any other. Openings of mounted aperture antennas are protected from environmental effects by dielectric covers. Aperture antennas have high gain and moderate bandwidth. Gain of aperture antennas increases with an increase in frequency. For constant aperture efficiency, the gain of aperture antenna is directly related to the square of operating frequency [1] [22].


(a) Horn antenna

(b) Reflector antenna

Figure 2. 5 - Aperture antennas [1]

As observed in Figure 2.5 above, aperture antennas have opening for electromagnetic waves path way. A receiver aperture antenna collects electromagnetic waves through its opening.

2.3. Antenna Array

Although there are some simple devices like mobile phone that can perform with single antenna, many recent wireless communication systems require improved performance such as narrow beam and highly directive radiation characteristics. These characteristics may not be achieved by using single antenna in the simplest way, because radiation pattern of single antenna is relatively wide and provide low values of directivity. However, improved characteristics of antennas may be achieved by either increasing the electrical size of a single antenna or by using different forms of antenna arrays. In most cases, increasing the electrical size of a single antenna to any desired value may no longer be practicable, rather using antenna arrays could be best solutions for most practical applications. Antenna arrays can provide higher gain, more directive radiation pattern, steerable and narrow main beam and other performance features. Highly directive antennas are required for many wireless communication applications such as long-distance communications, radar communications, sonar communications, etc. [26] [32].

Antenna array is a combination of two or more identical or non-identical radiating antenna elements arranged in a specified electrical or geometrical configuration. Most often, the radiating components in the array are identical in type and uniformly oriented for analytical and performance simplicity. Total radiated far-field of the array is determined by the vector sum of fields radiated by individual array elements. The far-field radiation pattern of antenna array depends on the use of different controlling mechanisms. These mechanisms include geometrical configuration, type and number of array elements, separation distance between array elements, excitation of individual array elements and relative orientation of individual array elements [1].

Array elements can be geometrically configured either in linear, circular, rectangular, spherical or planer fashion with equal or unequal spacing between them depending on design requirements. They can also be excited with in-phase or out of phase and equal or unequal amplitude current. The proper adjustment made on these array performance variables able to produce directive and narrow beamwidth main beam pattern [1] [26] [33].

The evolution of antenna array design started a few decades ago and is still ongoing research area to provide attractive and application-based radiation characteristics as desired as possible. Antenna arrays have a number of advantages including increased operational robustness, flexibility, custom formation and steering of beam forms, cost saving in implementations, etc. [34].

2.4. Antenna Array Performance Metrics

To satisfy the ongoing growth of data traffic and new application requirements of the current time wireless communication, different antenna array performance parameters are considered. The performance of antenna array is measured using different parameters. However, some of the parameters are related to each other. Antenna arrays are generally measured by their radiation pattern properties. The radiation pattern of antenna array is measured in relation to its radiation gain, SLL, beamwidth (HPBW or FNBW), directivity etc. [33].

Depending on the separation between the locations of antenna and observation point, radiation pattern can be determined in three different regions. These regions are reactive near field region, $R < 0.62\sqrt{D^3/\lambda}$, radiating near field (Fresnel) region, $0.62\sqrt{D^3/\lambda} \le R < 2D^2/\lambda$, and far field (Fraunhofer) region, $R > 2D^2/\lambda$. R is distance between antenna location and observation point in space, D is maximum dimension of antenna and λ is the wavelength [1]. In this thesis radiation pattern meant far field radiation pattern.

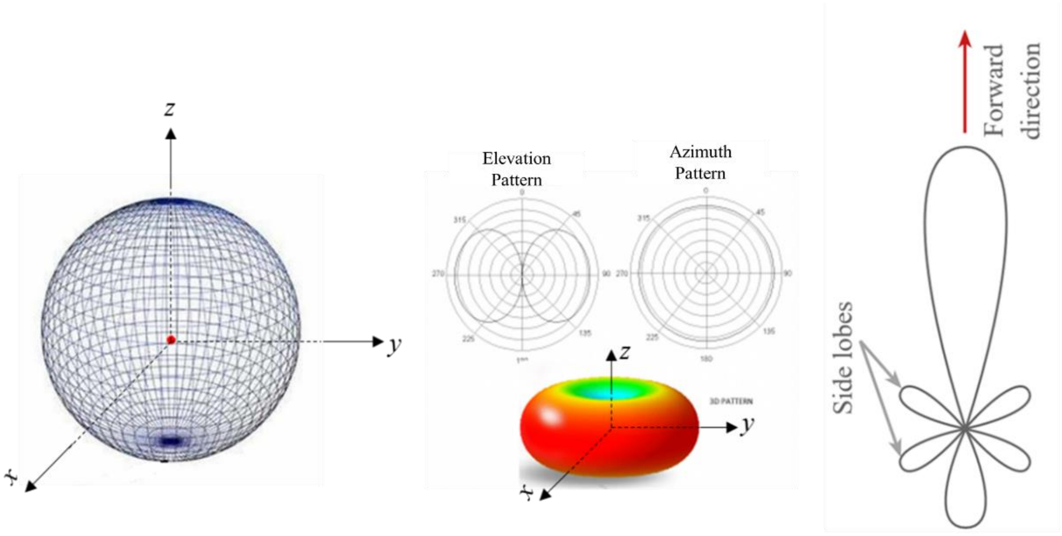
2.4.1. Antenna Array Radiation Pattern

Radiation pattern is the most basic antenna array performance measure. It is a mathematical description or a graphical illustration of spatial distribution of radiated energy of antenna array as a function of directional space coordinates. The radiation pattern can be presented in either polar, spherical or cartesian coordinate systems. The polar or spherical radiation pattern gives insight into the manner in which the antenna array actually radiates into the space, while the cartesian coordinate representation is useful to determine the parameters associated with antenna array pattern [22] [26]. In this thesis cartesian coordinate system is used to represent radiation pattern of antenna array of interest.

Antenna selection is the most critical task to be seriously considered to meet requirements of specific applications. Based on the symmetricity properties of radiation pattern, antennas are categorized into three types: isotropic radiator, omnidirectional radiator and directional radiator antennas. Ideally, isotropic radiator antennas are lossless and radiate uniformly to all directions with equal intensity irrespective of the direction of measurement. Isotropic radiators have ballshaped radiation as shown in Figure 2.4 (a) and are ideal radiators but they are used as reference to characterize practical antennas.

Omnidirectional antenna radiates around the antenna and can cover wider area. Omnidirectional antennas have non-directional pattern in some plane but have directional pattern in any orthogonal plane as shown in Figure 2.6 (b). Omnidirectional radiation pattern can be considered to be a special type of directional pattern. They are commonly used in FM radio coverage, cell phones and some other wireless applications. Wire antennas, specially dipole antennas are common omnidirectional radiators.

Directional antennas are practical radiators and can cover wider range than omnidirectional antennas. Directional antennas have narrow beamwidth that enable them concentrate and focus the available energy to the desired direction much more effectively than the former two radiators. Directional antennas are applicable in base station, satellite television and long-distance communications. Directional antenna does not cover its surroundings like omnidirectional antenna as shown in Figure 2.6 (c), rather it radiates in a specified direction [1].



(a) Isotropic (b) Omnidirectional (c) Directional

Figure 2.6 - Radiation Pattern of (a) Isotropic, (b) Omnidirectional & (c) Directional Antennas [1] [22]

Radiation pattern of antenna array can be theoretically determined for known gain or directivity of individual array elements and inter element spacing. The radiation pattern can be determined based on either field strength or power and can be shown in either linear or logarithmic scale [22].

Antenna radiation pattern is often observed from the side which is commonly known as vertical cut. This describes how the antenna radiates in the vertical plane. Observation from above or below forms horizontal cut and provides side way radiation information of the antenna. The vertical cut can be taken when elevation angle rotates 360 degrees and the azimuth angle is the observation direction in the x-y plane. In similar way, the horizontal cut is taken when azimuth angle rotates 360 degrees and azimuth angle is along the z-axis.

These cuts provide easy-to-read data of antenna’s radiation patterns and this thesis uses the above-mentioned definition of a vertical cut in all parts. Radiation pattern of antenna array is measured in terms of various parameters: radiation pattern lobes, SLL, beamwidth, radiation pattern nulls, etc.

2.4.1.1. Radiation Pattern Lobes

The radiation pattern of antenna array has different beam parts with different relative peak levels. These peaks are referred to as pattern lobes. The lobe with the highest peak level is main lobe or major lobe. Major lobe is formed when the radiation pattern of individual array elements sums up constructively in the direction of radiation. Major lobe can be rotated to any desired direction with phase difference of array elements. The whole radiated power may not be directed towards the desired direction, rather some part of the radiated power may be directed in undesired direction and concentrated in the form of lobes other than the main lobe. The other lobes of radiation pattern smaller than major lobe are referred to as minor lobes. They contain side and back (grating) lobes. Back lobes appear, sometimes with equal amplitude as main lobe, directly opposite to the major lobe when inter element spacing is equal to an integral multiple of the wavelength. Side lobes appear adjacent to major lobe and radiate in different direction than the main lobe. This radiation direction is undesired; therefore, the magnitude of side lobes should be reduced as much as possible as higher side lobe level causes sever interference and degrade array performance [1] [22].

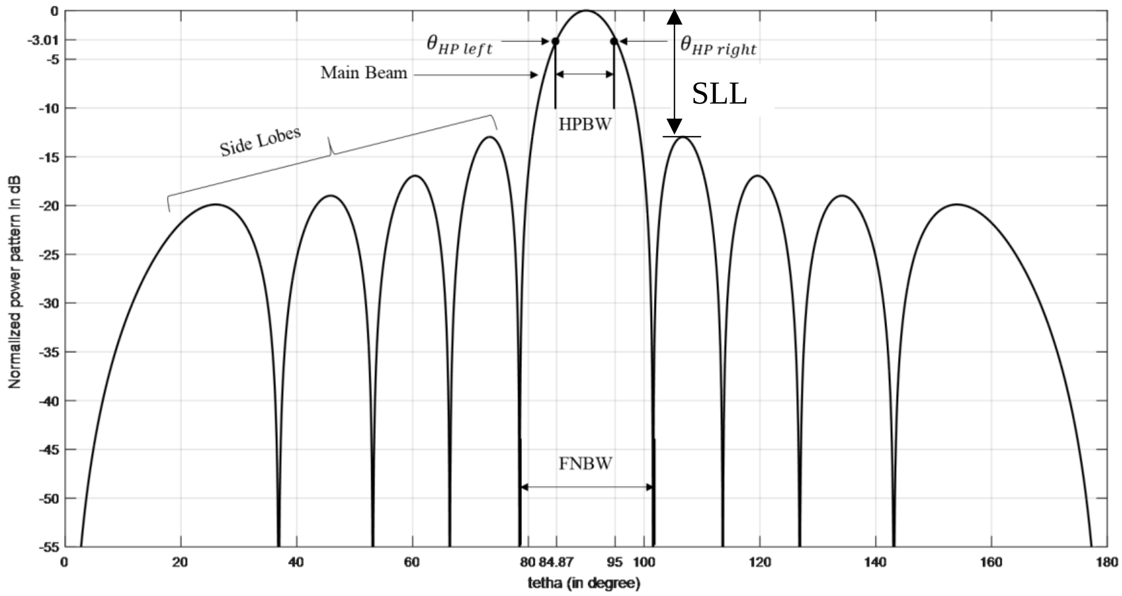


Figure 2.7 - Radiation pattern lobes and beamwidth

The antenna radiation is mathematically or graphically represented in terms of total radiated field or power. Graphical representation is used to determine different pattern parameters like SLL and beamwidth to quantify radiation pattern properties as shown in Figure 2.7.

2.4.1.2. Side–Lobe Level (SLL)

SLL is performance metrics of antenna array that measures how well the radiated power of the antenna array concentrated in the main beam. SLL is the relative height of the first side lobe down from the maximum point of the main lobe and mathematically expressed, in decibel, as the ratio of the peak of the side lobe to the peak of the main lobe [22].

$$SLL_{dB} = 20 \times log_{10}\left(\frac{|E_{total}(\theta,\phi)|}{|E_{total}(\theta,\phi)|_{max}} \right) \tag{2.3}$$

The peak SLL (PSLL) can be expressed by

$$\mathrm{PSLL}_{\mathrm{dB}} = \max\left(20 \times \log_{10}\left(\frac{|\mathrm{E}_{\mathrm{total}}(\theta,\phi)|}{|\mathrm{E}_{\mathrm{total}}(\theta,\phi)|_{max}} \right) \right) \tag{2.4}$$

2.4.1.3. Array Beamwidth

Beamwidth is a measure of the area of main beam to accurately indicate the desired target. Beamwidth measurement can be done in two common ways: between the null points of the main beam or between the half power points of the main beam. The beamwidth measurement between the null points is termed as first null beamwidth (FNBW) and the measurement between half power point is half power beamwidth (HPBW).

HPBW is the common performance measure of antenna array beamwidth and is the angular distance between half power points of the principal beam. HPBW provides valuable information for antenna comparison and usually an antenna is considered to operate properly within that angle. Half power points are points on the main beam where the main beam of the power pattern falls one-half of the maximum value or $1/\sqrt{2}$ of the field strength [22]. The mathematical expression of HPBW is given as:

$$\mathrm{HPBW} = |\theta_{\mathrm{HP\,left}} - \theta_{\mathrm{HP\,right}}| \tag{2.5}$$

Where $\theta_{\mathrm{HP\,left}}$ & $\theta_{\mathrm{HP\,right}}$ are respectively the left and right angles at which half power points are located.

2.4.2. Directivity

Directivity of an antenna array is the measure of the concentration of radiated power in a particular direction. In other words, directivity is the potential of antenna to direct the radiated power in a specified direction. Directivity is well improved by using antenna array. The directivity of individual array elements multiplied by the array factor provides directivity of the array. Directivity is a mathematical formula expressed as the radiated power by the array in a given direction compared to the radiated power by an isotropic radiator in the same direction.

$$D(\theta) = 4\pi \frac{\left|E_{total}(\theta,\phi)\right|^2}{\int_0^{2\pi}\int_0^{\pi}\left|E_{total}(\theta,\phi)\right|^2 \sin\theta \, d\theta \, d\phi} \tag{2.6}$$

Where $E_{total}(\theta,\phi)$ =far field radiated field and $D(\theta)$ = directivity of a given array.

2.4.3. Polarization

Polarization is the physical orientation of electromagnetic wave in free space. Polarization of antenna is taken to be the polarization of radiated or received wave in a given direction. For the case of non-specified direction, the direction of maximum gain is conveniently taken as antenna polarization. Different parts of antenna pattern may have different polarization due to the variation of polarization with distance from the center. Polarization of an electromagnetic vector describes the time dependent direction and comparative magnitude of the electric field vector. Thus, conventionally the polarization is described in terms of electric field vector. Electric field vector polarization can be known by observing the field along the direction of propagation [22] [30].

Polarization can have three forms, linear, circular or elliptical forms, despite the fact that, the first two forms can be derived from the later in special cases. Linear polarization of far-field wave should have the following properties to be said linearly polarized

- It must have only one component or
- It must have two 180^{o} out of phase orthogonal components or
- It must have integral multiple of 180^{o} out of phase orthogonal components.

There are antennas whose structure determines its polarization, such as a dipole. Dipole antenna is linearly polarized parallel to its orientation [35]. This thesis work focuses on linearly polarized antenna arrays.

2.4.3.1. Polarization Loss

The power of a received signal could be affected by polarization of antennas that form transmit/receive pair. Therefore, in order to collect a signal having maximum power, the polarization of receive antenna have to match the polarization of transmit antenna. The factor that matches polarization of the two antennas can be measured as

$$\rho = |\rho_t \rho_r|^2 \tag{2.7}$$

Where ρ_t & ρ_r represent the normalized polarization states of the transmit and receive antenna, respectively.

2.5. Types of Antenna Array

As described in sec 2.3, antenna array elements can be geometrically configured as linear, circular, planar, or conformal. Linear antenna array, which is the concern of this paper, can be formed by arrangement of array elements along a straight line. Whereas, circular antenna array are formed by arranging array elements in a ring structure. Planar arrays are linear arrays arranged in columns and rows with different distances between elements along the column and the row. They are formed by arrangement of array elements in a grid on a plane or surface. Planar arrays have two dimensions to shape and control the radiation pattern. Planar arrays are able to provide symmetrical pattern with reduced SLL and steer main beam towards any direction in space [1].

Conformal antenna array is an array designed to conform some non-planar surface of any form determined by non-electromagnetic factors. Conformal arrays can be planar depending on the surface in which antennas are arranged. The aim of conformal array is to integrate the antennas with some structures so that they could not be easily seen [36].

2.5.1. Linear Antenna Array

Design of linear antenna array is fundamental electromagnetic optimization problem of the current time. A linear antenna array consists of a number of similar antenna elements placed at regular intervals in a straight line as shown in Figure 2.8 to produce directional radiation pattern. These antenna elements are used in many communication and radar systems. Antenna arrays are generally characterized by their radiation pattern properties. The radiation pattern of antenna array is measured in relation to its radiation gain, SLL, beamwidth, directivity etc. [3] [37].

2.5.2. Types of Linear Antenna Array

Linear antenna arrays can be categorized based on array elements distribution as uniform and non-uniform linear arrays.

a) Uniform Linear Array

Array elements of uniform linear array are excited with currents of equal amplitude and the same progressive phase shift along the array axis. In uniform linear arrays, the array elements are equally spaced and each element is excited with equal magnitude and in-phase current. Though any value can be chosen for the enter element spacing between the array elements, to avoid grating lobe the enter element spacing of a linear array is chosen to be different from an integral multiple of the wavelength ($d \neq n\lambda$, n=1, 2, 3, ….) [1].

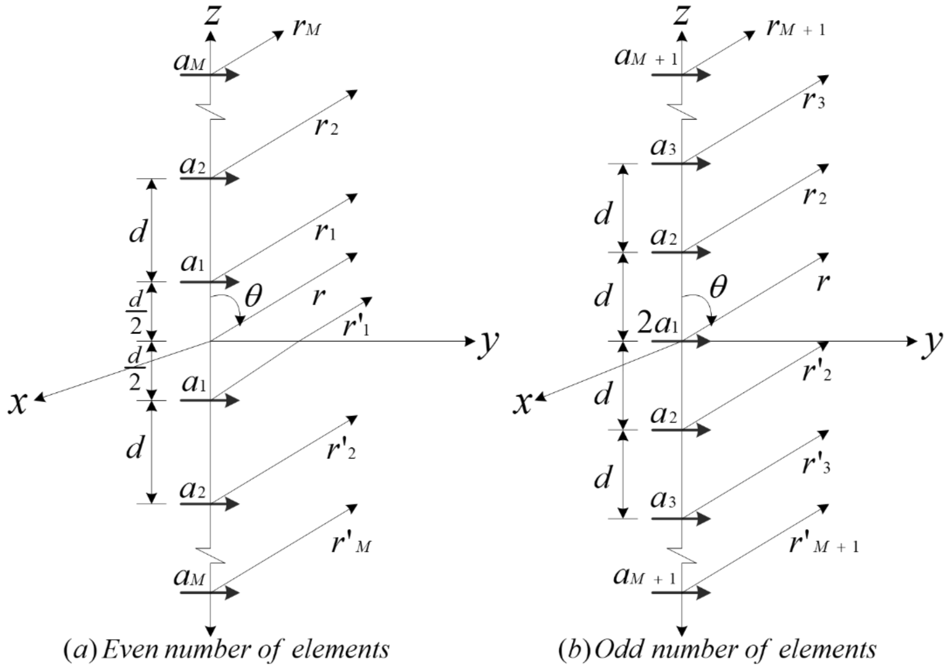


Figure 2.8 - Linear antenna array of even (a) & odd (b) number of elements

b) Non-Uniform Linear Array

Non-uniform linear antenna arrays are designed with non-uniformity either in excitation amplitude, excitation phase or inter element spacing or combination of all parameters among the array elements. This thesis focused on broadside non-uniform linear halfwave length dipole antenna array. The radiating antennas of broadside array are arranged along with array axis and the principal beam is normal to the array axis. Binomial and Dolph-Tschebyscheff arrays are common examples of non-uniformly excited broadside arrays [22].

2.5.3. Dipole Antenna Array

This thesis is concerned with non-uniform linear dipole array. Dipole antenna array can be designed in three different element arrangements. These different arrangements are side–by–side (parallel), colinear and parallel–in–echelon configurations [38].

Side–by–side configuration of dipoles is shown in Figure 2.9 below. In this configuration, current distribution is stable between dipoles; however, the enter element spacing design could become a problem. Inter element spacing of parallel dipole array requires careful design to avoid coupling effect within array elements.

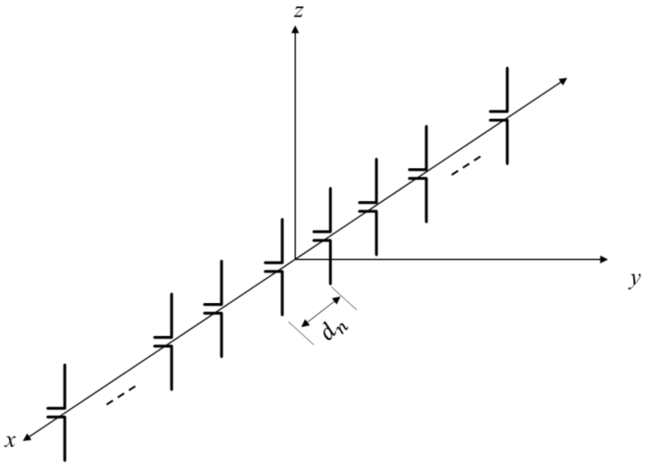


Figure 2.9 - Side-by-side or parallel dipole array.

Colinear dipole array is shown below in Figure 2.10. This configuration requires larger space along the array axis. The enter element spacing of colinear dipole array is measured between the center of dipoles. When the enter element spacing is very short, it introduces coupling among the elements.

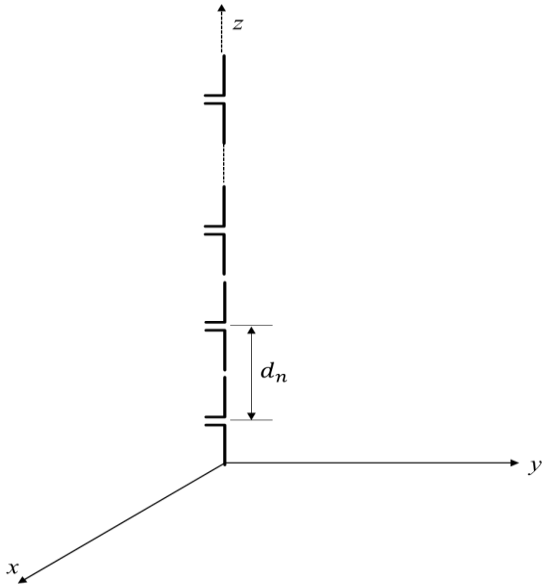


Figure 2.10 - Colinear dipole array.

Parallel–in–echelon dipole array has a specific angle that determines the dipole alignment direction. This alignment angle is often 45^o to provide similar performance to cross and co-polarizations in a cross–shaped dipole antenna. Parallel–in–echelon dipole array is shown in Figure 2.11, where dipoles are aligned with 45^o inclination and enter element spacing. The current distribution of parallel–in–echelon dipole array might become unstable and causes phase difference among array elements. As a result of this phase difference, mutual coupling will be difficult to estimate.

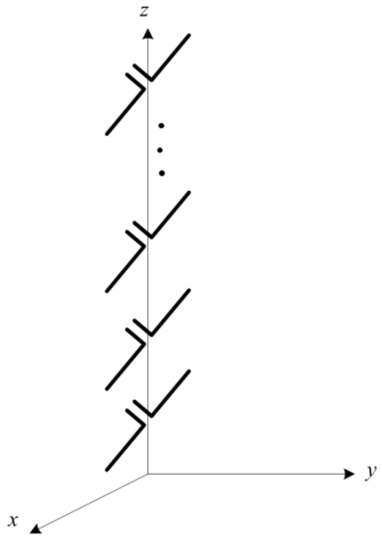


Figure 2.11 - Parallel - in - echelon dipole array

Chapter Three

Problem Formulation & Array Model

This chapter presents array modeling and mathematical formulation of linear halfwave dipole antenna array with colinear orientations. The individual array elements are thin and do not occupy considerable volume. The inter element spacing among the array elements is non-uniform. To alleviate coupling problem between adjacent array elements and suppress the appearance of grating lobe in the radiation pattern element spacing is designed to be approximately equal to half the wave length of the radiated or received signal of interest. If the inter element spacing is greater than a wave length, grating lobe will appear [39]. The array is considered to be at the transmit side. However, by the principle of reciprocity, it is possible to use a given antenna array as transmitter and receiver at the same time or independently. Hence, these and others initial points are considered for problem formulation in this work.

3.1. Problem Formulation

Traditional approaches for analysis and design of low side lobe arrays are based upon an array of point sources rather than practical full wave electromagnetic models of the array elements. The SLLs are controlled using the appropriate element weighting or spacing by using analytical or numerical synthesis methods for arrays with and without element patterns and with and without mutual coupling [13].

When non-uniform linear array is considered, total radiated field of the array at far–zone is the vector sum of the fields radiated by individual array elements. Excitation amplitude of array elements and array geometry are assumed to be symmetric with respect to the midpoint of the of the array. In the absence of ground plane, the total radiated far-field pattern in the horizontal y-z plane is described as the product of the element factor and the array factor. This expression is pattern multiplication rule [1] [21].

$$E_{total} = [ElementFactor] \times [ArrayFctor] \tag{3.1}$$

Where the array factor of a non-uniformly excited, non-uniformly spaced, symmetrical linear array is given by the expression [3]:

$$AF(\theta)=\begin{cases}\sum_{m=1}^{M} I_m \cos\left((m-0.5)kd_m\cos\theta+\beta\right), & N=2M,\ \text{even}\\ \sum_{m=1}^{M+1} I_m \cos\left((m-1)kd_m\cos\theta+\beta\right), & N=2M+1,\ \text{odd}\end{cases} \tag{3.2}$$

Where, $k=\frac{2\pi}{\lambda}$ is wave number,

λ is the wavelength of the radiated signal,

m is the element number,

d_m is interelement distance measured between the centers of adjacent array elements,

θ is the polar angle of the far-field measured from array axis,

β is the progressive phase difference of array elements,

I_m is the magnitude of current for the m^{th} element on either side of the array center

N is the total number of the array elements and

M is positive integer.

In this work, a broadside array of N=2M halfwave dipole array elements spaced a distance d_m and directed along the z – axis as shown in Figure 2.6 (a) is considered. The maximum radiation of a broadside array is normal to the array axis ($\theta=90°$, $\beta=0°$). Array factor defines the impact of the combination of the individual radiating antenna elements without considering the specific radiation pattern of elements [22].

The maximum array length of non-uniformly spaced – uniformly excited linear array has been determined as [40]:

$$L=\sum_{n=1}^{N-1} d_n \tag{3.3}$$

From this expression the inter element spacing of uniformly spaced array of the same number of elements and array length as non-uniform can be calculated as:

$$d = \frac{L}{N-1} = \frac{\sum_{n=1}^{N-1} d_n}{N-1} \tag{3.4}$$

Where N is the total number of array elements.

3.2. Proposed Method for Side Lobe Suppression

Recent antenna array synthesis methods brought promising achievements to produce attractive radiation pattern. Different methods have been applied to suppress the SLL of linear antenna array. Non-uniformly spacing, non-uniformly exciting array elements or applying both non-uniformities can reduce the SLL of the array [11] [41] [42]. SLL suppression is the basic array performance measure since reducing the SLL of an array can reject potential interference outside the main beam and avoid radiation power wastage.

In this thesis, in addition to the two non-uniformities, another SLL suppression method was applied. In this method, symmetrically positioned individual array elements are made to vary their polarization by changing their orientation with respect to the array normal to some arbitrary angles. Figure 3.1, shows the polarization variation of uniformly spaced 2M array elements in which symmetrically placed outermost array elements are rotated about the array axis with arbitrary angle and form co-polarization and cross-polarization radiation components. The radiation pattern of the rotated array elements is expected to make interference in the location of side lobes. This interference can further suppress the SLL as will be show in simulation results. Hence, this approach provided another array modeling variable to control the radiation characteristics.

Varying the orientation of the array elements with respect to the array normal can change the gain and polarization of the element pattern. Rotation of the array elements will result in polarization difference from non-rotated array elements. Hence, in this work polarization ($\hat{\rho}$) is taken into account by considering element pattern of individual array elements in problem formulation given in equation (3.6) below.

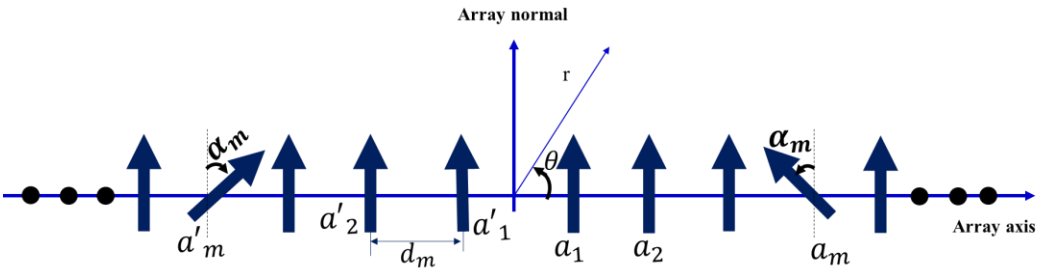


Figure 3.1 - polarization variation of 2M-elements dipole array with rotated external elements.

As described above rotated array elements form co–polarized and cross–polarized radiation components as shown in Figure 3.2. The co–polarized radiation components are add up constructively with radiation pattern of the rest of array elements towards the radiation direction and the cross–polarized components cancel each other. The cancellation of cross–polarized radiation components is due to the fact that flow of current through the rotated elements propagate in opposite directions.

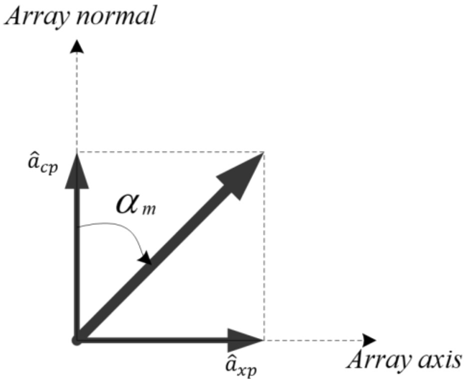


Figure 3.2 - Co–polarized (cp) & Cross–polarized (xp) components of rotated array elements.

The total radiated far–field of a *z*–oriented non-uniform linear array of halfwave length dipoles of which some are rotated is derived in y-z plane as:

$$E_{total}(\theta, I, d, \hat{\rho}) = \sum_{m=1}^{M} \left[\left(\hat{a}_{cp} \cos \alpha_m + \hat{a}_{xp} \sin \alpha_m \right) EF(\theta) \times AF(\theta) \right] \tag{3.6}$$

Where $\hat{a}_{cp}$ & $\hat{a}_{xp}$ are unit vectors along the co-polarized and cross-polarized components of the rotated elements respectively and α_m is an arbitrary angle to which individual array elements are rotated.

In this expression the total radiated field is defined as a function of polarization ($\hat{\rho}$) in addition to the commonly known variable like polar angle (θ), element weighting (I),inter element spacing (d) and number of array elements.

In order to obtain approximate parameters in this work, genetic algorithm optimization tool is used. Optimization is a process to regulate inputs or features of a device, mathematical expressions, or experiment to obtain minimum or maximum result [43].

The fitness (objective) function formulated to suppress the SLL of symmetrically configured linear antenna array is derived from the far-field expression given in Equation (3.6) above.

$$fitness = min(PSLL) \tag{3.7}$$

Where PSLL is peak SLL and defined by

$$PSLL = max\left(20 \times log_{10} \left| \frac{E_{total}(\theta)}{max\left(E_{total}(\theta)\right)} \right| \right) \tag{3.8}$$

3.3. Side Lobe Suppression Using Genetic Algorithm

Antenna array radiation characteristics improvements are the requirements of every time antenna researchers. To meet design requirements, antenna researchers employed different optimization tools that enable them effectively design antenna arrays. The optimization tools are used not only to synthesize arrays that satisfy design specifications but also to improve existing designs. Many researches have been conducted to utilize optimization tool that efficiently search for possible optimum solutions. GA is among these tools.

GA was invented by John Holland in the 1960's with a goal of biological-based artificial system design using natural adaptation principle [43]. GA is a powerful and widely used nature based random search and numerical optimization method. It is used to generate multiple solutions to optimization problems. GA is categorized to a family of evolutionary algorithms, that produces possible solutions to optimization problems using procedures stimulated by natural evolution; like inheritance, mutation, selection, and crossover. GA can solve many large complex problems where other methods have experienced difficulties such as large-scale combinatorial optimization problems and real-valued parameter estimations within complex search spaces damaged with many local optima [44].

GA is a way to solve constrained and unconstrained problems based on natural selection, which is driving process of biological evolution. Hence, GA can also solve mixed integer programming problems, where some components are constrained to be integer-valued. GA repeatedly modifies a population of individual solutions. At each search step, GA randomly selects individual parents to from current population and uses them to produce the children for the next generation. Over consecutive generations, the population advances toward an optimal solution. GA can be applied to solve a various optimization problem that cannot be solved using standard optimization algorithms, including discontinuous objective function, non-differentiable, stochastic, or highly nonlinear [37].

GA is simple to understand and the computer code is easy to write. GA is powerful and efficiently employed for

- Large, Complex and poorly understood search space
- Scarce domain knowledge or difficult expert knowledge to encode to narrow search space
- Unavailable mathematic analysis
- Failure of traditional search methods.

The evolutionary process of GA starts by randomly generating individual populations. In each generation, multiple individuals are selected randomly based of the specified fitness function, breed using crossover and modify using mutation to form new individual population. Hence, genetic algorithm involves three main sets of rules or operations to create the next generation from the current population [43] as defined below:

- ***Selection*** – a step to decide the fittest chromosomes in the initial population to survive and become parents of the next generation.
- ***Crossover*** – swap a section of genes between two selected parents, combine two parents and exchange genetic information to form children for the next generation.
- ***Mutation*** - use random variations to individual parents for children formation.

GA is different from classical, derivative-based, algorithms mainly in two ways:

1. GA produces a population of points in each repetition. 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.

3.3.1. Generalized Flow Chart of GA

The operation sequence of GA can be described by a simplified flow chart as shown in Figure (3.3):

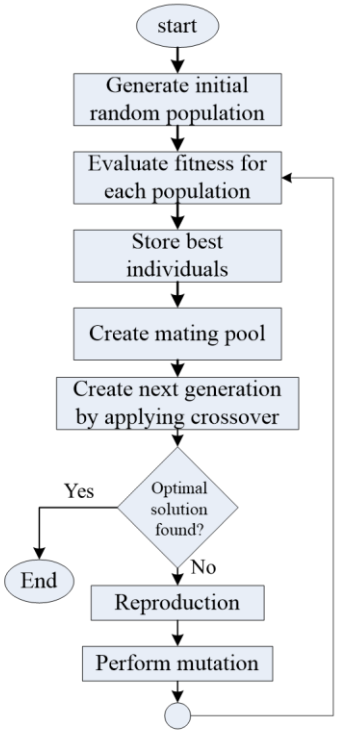


Figure 3.3 -Reproduction Cycle of GA [44]

The cycle is repeated multiple times until a condition for termination is met.

3.3.2. Parameters of Genetic Algorithms

The search performance of GA is greatly determined by the optimization tool parameter settings. These parameters control the run time, population and reproduction of GA. The main parameters include; population size, mutation rate and recombination type [43] [44].

3.3.2.1. 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 amount of individual variations in the initial population and increase the amount of fitness evaluation. The population size is related to number of chromosomes and depend on required applications.

3.3.2.2. Crossover Rate

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, crossover rate is usually high and depends on specified application.

3.3.2.3. 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 & 0.1is used for most applications.

For all simulation cases, the iterations of the GA optimization tool are terminated with pre-set stopping criteria. The populations 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 are lower or equal with the first side lobe.

3.4. Overview of MATLAB

MATLAB (Matrix Laboratory) was developed by MathWorks, Inc. and is a popular, user-friendly and widely used high-level computational language. MATLAB is used for different applications including, arithmetic and logical computations, algorithm development, modeling, simulation, prototyping, data analysis, visualizing, engineering graphics and development of graphical user interface. It is much easier to use than other high-level languages most expressions are computed in plane text format. MATLAB has toolboxes that perform specific tasks to satisfy requirements of users by user friendly commands and interfaces [45].

Moreover, MATLAB is used for signal processing and communications, image and video processing, control systems, test and measurement, computational finance, and computational biology. More than a million engineers and scientists in industry and academia use MATLAB. In this thesis, MATLAB R2015a software is used for simulation and optimization of linearly polarized linear halfwave dipole antenna arrays.

Chapter Four

Simulation Results and Discussion

This chapter deals with simulation results and discussion associated with them. Simulation is carried out for uniformly spaced–uniformly excited, uniformly spaced–non-uniformly excited, non-uniformly spaced–uniformly excited and non-uniformly spaced–non-uniformly excited 10–element linear arrays using MATLAB. Simulation of the above-mentioned linear array have been carried out in two steps. In the first step simulation is performed by changing the rotation angle of symmetrically located array elements until promising result is obtained. When array elements located around the center of array axis are rotated, the level of side lobes increased as compared to radiation pattern of uniform array. On the other hand, rotating symmetrically located outer most array elements show reduction of sidelobe levels. With this approach substantial side lobe level reduction is observed when the rotation angle of array elements is between 30° and 55°.

In the second step, for the same type and number of arrays the fitness function is passed through GA optimization toolbox to search for optimum angle of rotation. Finally, each simulation result is compared with each other and with uniform linear array of the same number of elements. For all cases simulation has been don with MATLAB version 8.5 (2015a) software.

4.1. Simulation Result of Uniformly Spaced–Uniformly Excited Array

Halfwave dipole array is simulated using MATLAB and radiation pattern was plotted. In this simulation, uniform broadside linear array with inter element spacing of 0.5λ was considered. This section presents simulation result of z-directed 10-element halfwave dipole antenna array.

Orientation of array elements is shown in Figure 4.1. From this Figure it can be observed that the optimal angle of rotation of the externally placed two array elements in each side is 50°. That means the 4th and 5th dipoles from the right side and their symmetric counter parts (4’ and 5’) dipoles are rotated by 50° angle of rotation.

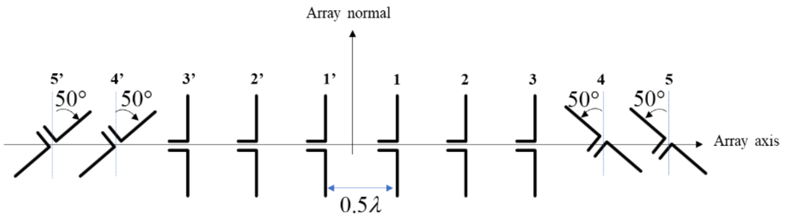


Figure 4.1 - Orientation of uniformly spaced 10 elements array.

The radiation pattern plot shown in Figure 4.2 shows simulation result of uniform z-directed linear array without rotation of elements and optimally rotated elements by GA optimization tool. Array elements are uniformly excited and uniformly spaced. The radiation direction is broadside. GA optimization tool find angle of rotation of symmetrically located outermost array elements. From the Figure it can be observed that radiation pattern with rotation of some of array elements has smaller side lobe level than uniform array for the same number of array elements and similar inter element spacing. From this observation it can be deduced that changing orientation of symmetrically placed two outermost elements able to reduce SLL.

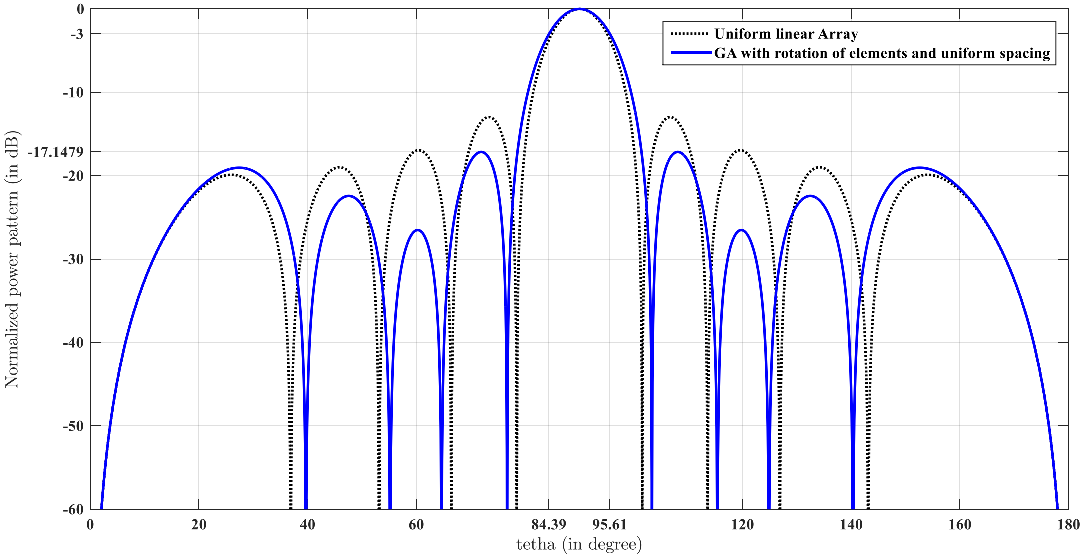


Figure 4.2 – Radiation pattern of uniform array & optimum angle of rotation linear array

Numerically the SLL is reduced from -12.9662 dB to -17.1479 dB with cost of 1.02° HPBW increase as shown below in Table 4.1.

Table 4.1- SLL & HPBW of 10 element uniform array with rotated elements

Array Type	SLL (dB)	HPBW (°)
Uniformly spaced – uniformly excited	-12.9662	10.2
GA- Uniformly spaced – uniformly excited with rotated elements	-17.1479	11.22

4.2. Simulation Result of Non-Uniformly Spaced – Uniformly Excited Array

SLL of antenna array depends on the spacing between array elements. Thus, variation of inter element spacing has direct effect on the characteristics of SLL, optimum design can be able to suppress it. In addition to optimally placing array elements, optimally rotating some of array elements can further suppress SLL. To obtain optimum values of inter element spacing and rotation angle of array elements, GA optimization tool has been used for equally excited linear array.

From problem formulation in equation (3.3), the normalized far-zone radiated electric field of non-uniformly spaced linear array can be expressed as a function of inter element spacing and polarization of array elements. This array has been considered to be symmetric about the center in terms of position of elements.

Figure 4.3 below show orientation 10 element half wave dipole array and optimum element spacing. Inter element spacing is normalized with respect to wavelength (λ).

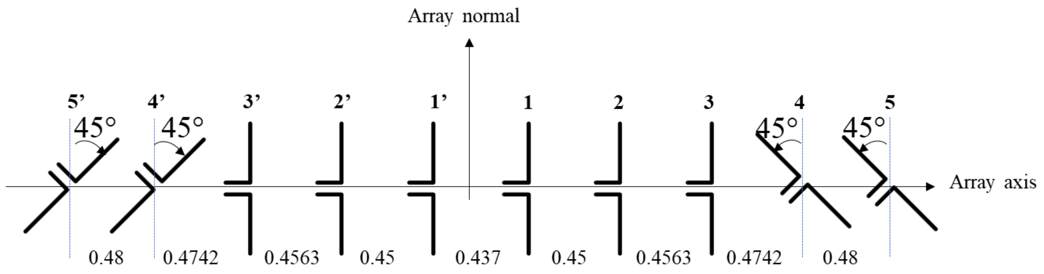


Figure 4.3 - Orientation & inter element spacing of non-uniformly spaced 10 elements array.

Figure 4.4 given below shows comparison of simulation results of radiation pattern of uniformly spaced, non-uniformly spaced – uniformly excited and non-uniformly spaced – uniformly excited with rotated halfwave dipole antenna array. GA optimization tool has been applied to find optimum inter element spacing and rotation of externally located array elements.

As observed from Figure 4.4, non-uniform inter element spacing of linear array play prominent role to suppress SLL with significant figure as compared to uniformly spaced array. When some externally positioned elements of non-uniformly spaced array are rotated to an optimum angle of 45° from array normal, SLL is further suppressed substantially. This result shows that orientation of dipoles in the array considerably impact their separation distance. When separation pacing is much smaller the half wave length, it is vulnerable for coupling between rotated and unrotated elements. On the other hand, when separation distance is comparable with the wavelength of the signal, grating lobe start to grow up. To avoid these undesirable effects, inter element separation is design somehow comparable to half wavelength, i.e., slightly greater or less than half wavelength.

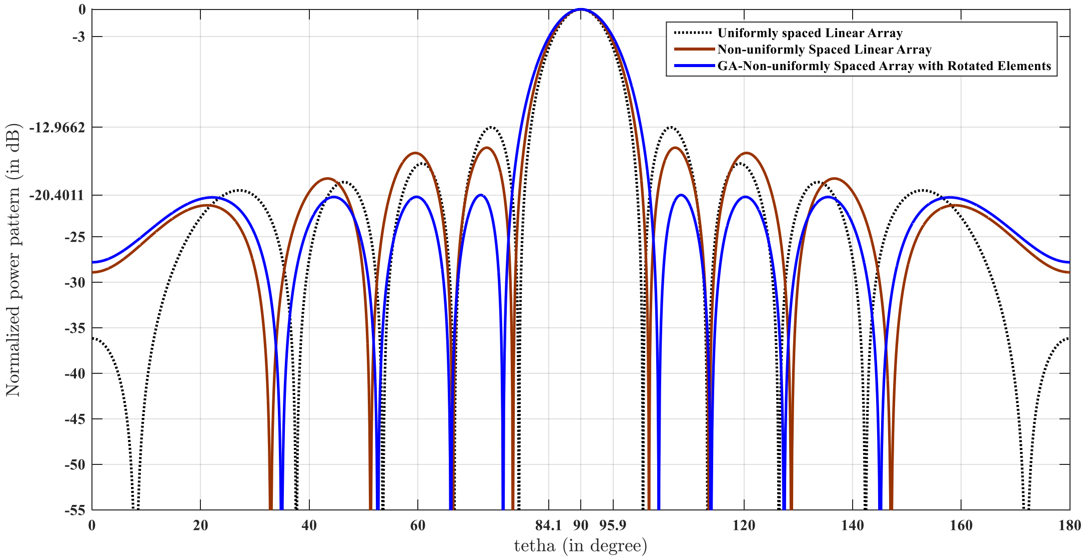


Figure 4.4 - Radiation Pattern of uniformly spaced, non-uniformly spaced and non-uniformly spaced with rotated elements array for N=10.

Tables 4.2 below presents optimum angle of rotation, SLL and HPBW of a 10-element non-uniformly spaced halfwave dipole linear array.

Table 4.2 – SLL & HPBW of non-uniformly spaced array with rotated elements

Array Type	SLL (dB)	HPBW (°)
Uniform spaced – uniform excited	-12.9662	10.2
Non-uniformly spaced – uniform excited	-15.2029	10.88
GA-Non-uniformly spaced with rotated elements	-20.4011	11.81

The numerical values of Table 4.2 show significant reduction of SLL as a result of optimal positioning of elements and rotation of symmetrically placed four exterior elements to an optimum angle of 45°.

4.3. Simulation Result of Uniformly Spaced – Non-Uniformly Excited Array

Variation of excitation amplitude of individual array elements has the ability to change the radiation characteristics and suppress SLL of antenna array. The normalized total far-field radiation pattern of unequally excited halfwave dipole antenna array can be derived from the general equation of problem formula given in equation (3.3) and can be described as a function of excitation amplitude and polarization of array elements. Hence, GA optimization tool has been used to find optimal values of excitation amplitude and rotation angle of array elements. In this case, excitation amplitude is considered to be normalized with respect to the max value, which will then be within the range [0,1] and symmetric about the center of the array axis.

The inter element spacing is uniform, d=0.5λ and the array length is the same as the above simulation. The orientation of elements and their respective excitation amplitude of a 10-element array is shown in Figure 4.5.

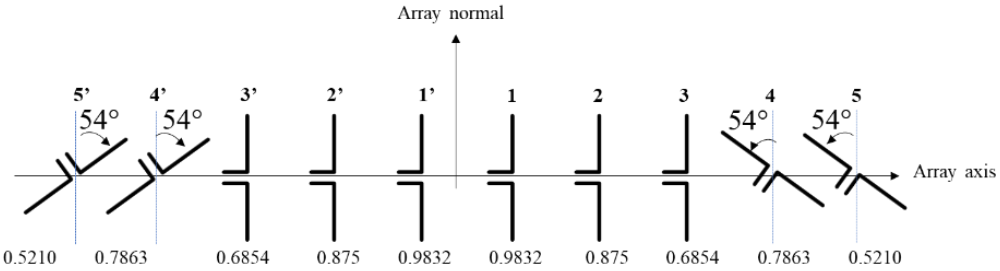


Figure 4.5 - Orientation & excitation amplitude of non-uniformly excited 10 elements array.

The simulation result of N=10 z-directed symmetrical linear array is given below in Figure 4.6. It shows the radiation pattern results of uniformly spaced – uniformly excited linear array, uniformly spaced – non-uniformly excited linear array and uniformly spaced – non-uniformly excited linear array with rotated elements. Comparing these three radiation pattern results, the SLL of uniformly spaced – non-uniformly excited linear array with rotated elements is smallest than the others for the same number of array elements and array length. This indicates that when some of externally positioned elements are rotated from array normal, SLL is further suppressed with significant amount in comparison with uniformly excited and non-uniformly excited array.

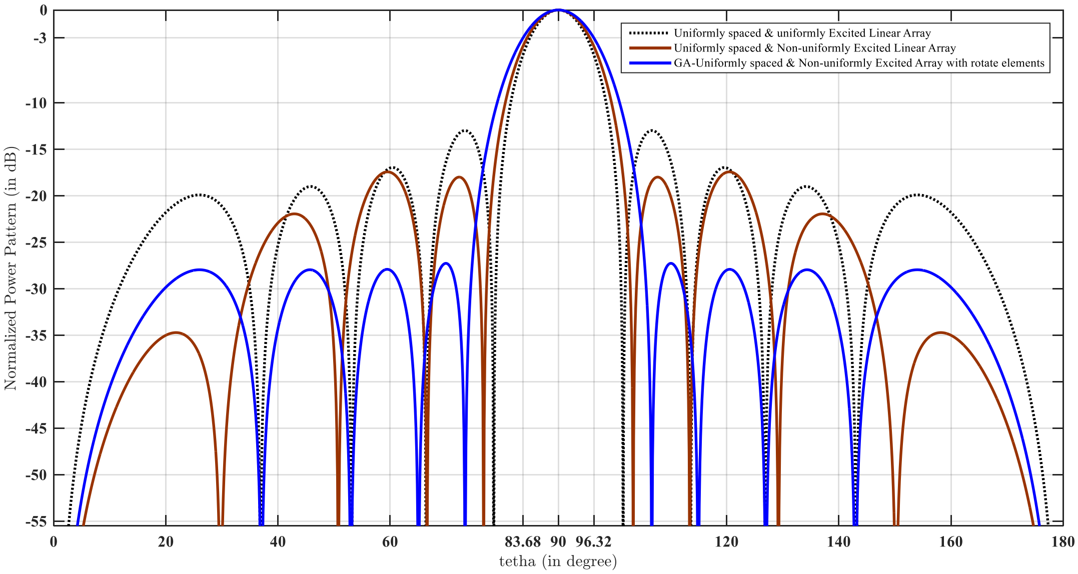


Figure 4.6 - Radiation Pattern of uniformly spaced, non-uniformly excited and non-uniformly excited with rotated elements array for N=10.

Table 4.3 below presented SLL and HPBW comparison of uniformly spaced – uniformly excited linear array, uniformly spaced – non-uniformly excited linear array and uniformly spaced – non-uniformly excited linear array with rotated array elements. GA optimization tool generates optimum excitation amplitude and angle of rotation of four symmetrical outermost elements.

Table 4.3 - SLL & HPBW of non-uniformly excited array with rotated elements

Array Type	SLL (dB)	HPBW (°)
Uniformly spaced – uniformly excited	-12.9662	10.2
Uniformly spaced – Non-uniformly excited	-18.3920	11.2
GA - Non-uniformly excited with rotation of elements	-27.2494	12.64

From this table it can be observed that variation in excitation amplitude for uniform orientation can have the potential to reduce side lobe level. Comparing the three numerical results of Table 4.2 and Table 4.3, non-uniform excitation is much prominent to reduce SLL over non uniform spacing. This is because excitation amplitudes have direct impact on magnitudes of lobes of radiation pattern.

4.4. Simulation Result of Non-Uniformly Spaced–Non-Uniformly Excited Array

Simulation result presented in this section is obtained when inter element spacing and excitation amplitude are both non-uniform. For this case the normalized far field radiation pattern expression can be defined as a function of inter element spacing, excitation amplitude and polarization of array elements. Before passing the fitness function of this expression through GA optimization tool, analysis is made for previous results. When element spacing from Table 4.2 and excitation amplitude from Table 4.3 are substituted in the function without changing the orientation of individual array elements, the first side lobe is reduced to -22.9321dB. However, the second and third side lobes are larger than the first lobe. The analysis also shows relatively wider HPBW, i.e., 13.6°.

Keeping the element spacing and excitation amplitude unchanged as in the above discussion and varying the orientation of individual array elements in the range of 35° to 46°, the result shows significant reduction in first SLL that ranges -30dB to 50dB. The HPBW does not relatively become too much wider, it ranges 12.5° to 13°. However, secondary and tertiary side lobes keep on increasing above the first side lobe.

From these two analysis results, it can be concluded that all spacing, excitation amplitude and angle of orientation of array elements must be varied at the same time to optimally reduce SLL. Varying these parameters and employing GA optimization tool to search for optimal values of spacing, excitation and rotation angle of array elements, SLL will be reduced.

Both inter element spacings and excitation amplitudes are normalized with respect to wave length and maximum excitation amplitude, respectively. For N=10 z-directed linear symmetrical array, in which both geometry and excitation are symmetric, the orientation of the array is given below in Figure (4.7).

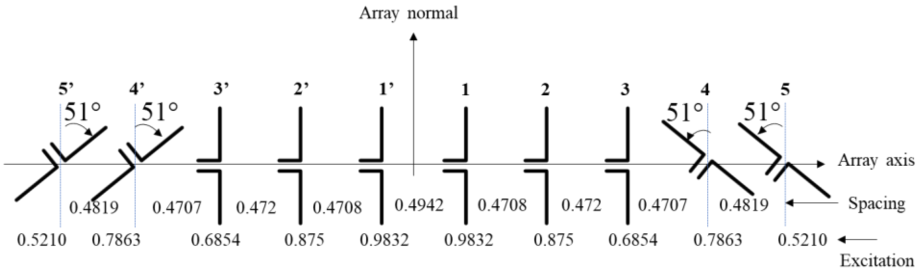


Figure 4.7 – Orientation, spacing and excitation amplitude of non-uniform 10 elements array.

The far-field radiation of non-uniform array with rotated array elements is given below in Figure 4.8.

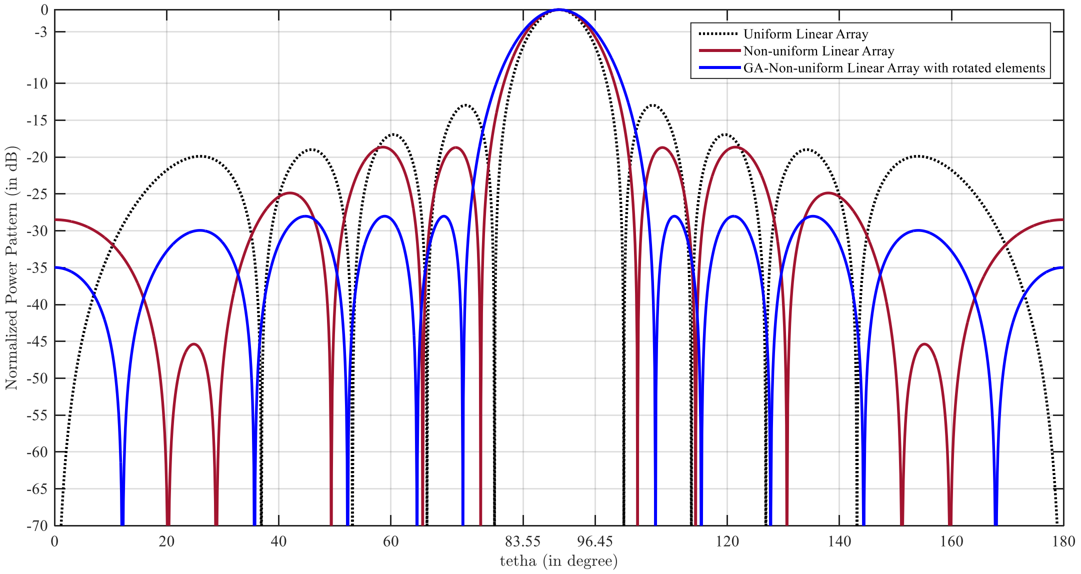


Figure 4.8 - Radiation Pattern of non-uniform array for N=10

When the array elements are non-uniformly spaced and non-uniformly excited at the same time and externally positioned array elements are rotated by application of GA optimization tool, the resulting radiation pattern has lowest SLL than others. The minimum achievable SLL of this case is -28.0193dB for 12.9^{o} half power beamwidth.

The excitation amplitude distribution, inter element spacing, SLL and HPBW and rotation angle of a 10-element halfwave colinear dipole array are numerically tabulated in Table 4.4 and 4.5 below. The inter element spacing is normalized with respect to wavelength. Due to symmetricity of excitation amplitude and element position, right half side values are presented.

Table 4.4 - Inter element Spacing, excitation amplitude and angle of rotation of non-uniform linear array for 10 elements.

Array Elements	1	2	3	4	5
Inter Element Spacing	0.4942	0.4708	0.472	0.4707	0.4819
Excitation amplitude	0.9758	0.8124	0.6932	0.7822	0.5969
Angle of rotation (deg.)	0	0	0	51	51

Table 4.5 - Numerical values of, SLL &HPBW of non-uniformly spaced–non -uniformly excited linear array for 10 elements.

Array type	SLL (dB)	HPBW (°)
Uniformly spaced – uniformly excited	-12.9662	10.2
Non-uniformly spaced – non-uniformly excited	-18.7056	11.64
GA-Non-uniformly spaced–non-uniformly excited with rotated elements	-28.0193	12.9

4.5. Comparison of all Simulation Results

In this section all results are compared for similar array size and array length. Uniform linear array is taken as reference to compare the other SLL.

Figure 4.9 depicted comparison of all types of simulation works. As observed from the Figure SLL of non-uniformly spaced – non-uniformly excited linear array is smallest, in ordered list, followed by non-uniformly excited linear array, non-uniformly spaced linear array and uniform linear array. However, as expected decreasing order in SLL conversely increase HPBW. The widening of HPBW enables an array to cover wider area but not longer distance as compared to arrays with very narrow beamwidth.

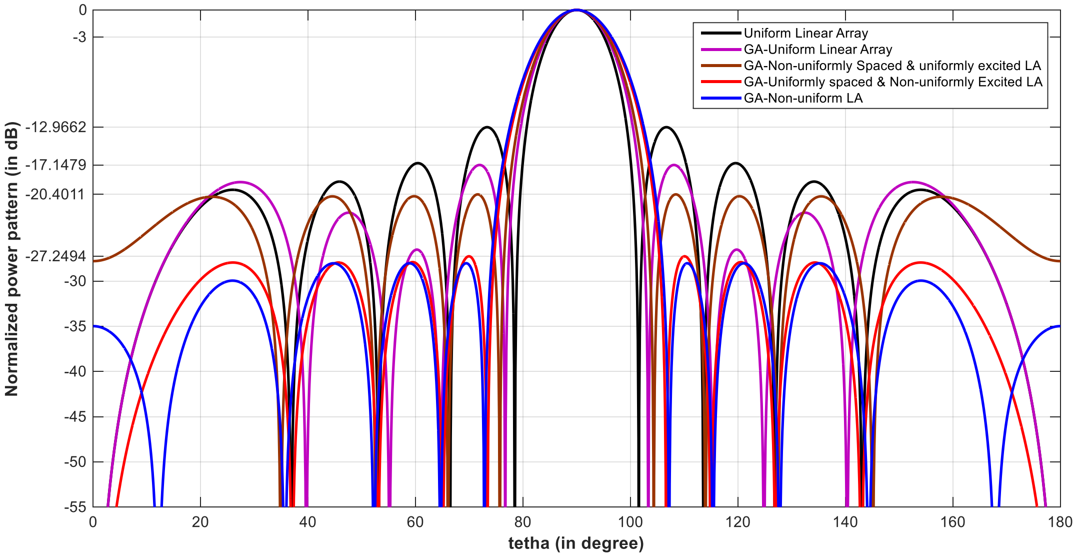


Figure 4.9 - Comparison of all array types for same aperture & array size

Numerical values of these array performance metrics are provided in table 4.9 below.

Table 4.6 - Summary table for comparison of SLL and HPBW of all simulation results

Array type	Angle of Rotation	SLL (dB)	HPBW (°)
Uniform spacing – uniform excitation	0	-12.9662	10.2
GA-uniform spacing – uniform excitation	50	-17.1479	11.22
GA-Non-uniform spacing – uniform excitation	45	-20.4011	11.8
GA-uniform spacing – non-uniformly excitation	54	-27.2494	12.64
GA-Non- uniform spacing – non-uniformly excitation	51	-28.0193	13

As can be observed from Figure 4.9 and Table 4.6 as well, the result of entirely non-uniform linear array with rotted elements does not show significant difference. This may be probably due the increased amount of instability in entirely non-uniform array, that is caused by non-uniformities in all of the parameters. In all simulations, the number of symmetrically positioned rotated array elements are 4. Symmetrically located array elements were rotated for the same angle of rotation. In this case, 2 elements from each side rotated with the same angle.

Chapter Five

Conclusion and Recommendations for Future Works

5.1. Conclusion

In this thesis, side lobe reduction of linearly polarized antenna arrays was studied. Simulation of halfwave dipole antenna array was performed using MATLAB. It is known that reducing SLL of antenna array saves radiation power and reduce potential interference in neighboring radiating devices.

Simulation of uniform and non-uniform arrays with and without proposed SLL suppression method of arbitrary array elements rotation was conducted and results are compared. Rotating some of array elements can produce a radiation pattern with low SLL. The proposed array element rotation method together with optimization in inter element spacing and excitation amplitude show promising SLL reduction. From simulation results obtained in chapter 4 as SLL further reduced, HPBW increased. This is expected study challenge, because SLL and HPBW have inverse relation. With observation of simulation results, the following conclusions can be made.

- Changing the orientation of outermost array elements of linearly polarized antenna arrays significantly reduce SLL.
- Genetic Optimization tool can improve SLL reduction by optimizing inter element spacing, excitation amplitude distribution and array element rotation angle.
- SLL is reduced without considerable increase in HPBW.

The proposed technique showed effective reduction of SLL without significantly degrading other radiation characteristics of the array.

5.2. Recommendation for Future Work

This thesis is limited to simulation of halfwave dipole antenna arrays. In addition to dipole array,

- Improvement linearly polarized array other than half wave dipole applying array element rotation concept.
- Performance improvement in planar array of finite length dipole using polarization variation of array elements.
- SLL suppression in circularly polarized antenna array by polarization variation of array elements.
- SLL suppression of phased array antennas employing polarization variation of array elements

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Appendix

Element factors of halfwave dipole antenna

Consider a uniform linear array of N-elements arranged along the z-axis to radiate in the broadside direction. The radiation behavior of a single antenna element is identified by the element pattern and characterized by its element factor. The element factor can be derived from the direction cosines.

For a half wave dipole along the x – axis with maximum excitation current I_m, the element factor has both θ and ϕ components, which are

Table App-1 - Element factors of halfwave dipole antenna at different axes.

Axis	Far-zone Element Factor	Normalized Element Factor
x	$EF_\theta = \frac{j\eta I_m e^{-jkr}}{2\pi r}\left[\frac{\cos\left(\frac{\pi}{2}\sin\theta\cos\phi\right)}{1-\sin^2\theta\cos^2\phi}\right]\cos\theta\cos\phi$	$EF_{\theta n} = \left[\frac{\cos\left(\frac{\pi}{2}\sin\theta\cos\phi\right)}{1-\sin^2\theta\cos^2\phi}\right]\cos\theta\cos\phi$
	$EF_\phi = -\frac{j\eta I_m e^{-jkr}}{2\pi r}\left[\frac{\cos\left(\frac{\pi}{2}\sin\theta\cos\phi\right)}{1-\sin^2\theta\cos^2\phi}\right]\sin\phi$	$EF_{\phi n} = \left[\frac{\cos\left(\frac{\pi}{2}\sin\theta\cos\phi\right)}{1-\sin^2\theta\cos^2\phi}\right]\sin\phi$
y	$EF_\theta = \frac{j\eta I_m e^{-jkr}}{2\pi r}\left[\frac{\cos\left(\frac{\pi}{2}\sin\theta\sin\phi\right)}{1-\sin^2\theta\sin^2\phi}\right]\cos\theta\sin\phi$	$EF_{\theta n} = \left[\frac{\cos\left(\frac{\pi}{2}\sin\theta\sin\phi\right)}{1-\sin^2\theta\sin^2\phi}\right]\cos\theta\sin\phi$
	$EF_\phi = -\frac{j\eta I_m e^{-jkr}}{2\pi r}\left[\frac{\cos\left(\frac{\pi}{2}\sin\theta\cos\phi\right)}{1-\sin^2\theta\sin^2\phi}\right]\cos\phi$	$EF_{\phi n} = \left[\frac{\cos\left(\frac{\pi}{2}\sin\theta\cos\phi\right)}{1-\sin^2\theta\sin^2\phi}\right]\cos\phi$
z	$EF_\theta = \frac{j\eta I_m e^{-jkr}}{2\pi r}\left[\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta}\right]$	$EF_{\theta n} = \left[\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta}\right]$

Where $\eta = 120\pi = 377\Omega$ the intrinsic impedance of free space,

The total normalized radiated field of an N-element dipole array along the z-axis is the product of the element factor and the array factor.