DESIGN & OPTIMIZATION OF AN ANTENNA ARRAY FOR WIMAX BASE STATION

MCS

By

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ABSTRACT

Conventional base station antennas in existing operational systems are either omni-directional or sectorized. The greater part of the transmitted signal power is radiated into directions other than toward the specific user. This causes interference, reduces efficiency and the range of coverage. Especially in new broadband services as WiMAX, where the user front-end is very simple, it becomes necessary to provide every user with a specific beam offering enough gain to increase the range. It is also important to reduce interference by other users or services by means of beam forming in a way, that either the side lobe attenuation of the base station antenna array as a whole is optimized or by null steering. In rural areas whole 360° degrees coverage around the base station is desired. This leads to the solution introduced here of circular antenna arrays, a setup which can also be used for direction finding.

The project is to design an eight array dipole antenna. The antenna array consists of n vertical dipoles equally spaced on a ring with diameter d. A power-combiner/ divider network is connected to the feed point of every dipole with m inputs/outputs according to the number of wanted coinstantaneous beams or null directions. For each independent beam direction the weights of the amplitudes and phases have to be calculated and optimized. The adjustment can be performed directly by phase shifters and attenuators in the RF-region or after linear down-conversion and analog to digital conversion by a DSP.

DECLARATION

It is declared that the material contained within this thesis is our own original work and has not been submitted to this or any other university before. It is also declared that this thesis is the intellectual property of Department of Electrical Engineering, Military college of Signals, National University of Sciences and Technology, Rawalpindi.

DEDICATION

To our Parents and Teachers

ACKNOWLEDGEMENTS

The most important acknowledgment, by far, is to ALLAH, the Almighty, who gave us the courage to complete our final year project successfully.

We owe a very special debt to our advisor Asst Prof. Zeeshan Zahid who spared his precious time and guided us in the best possible way. It was his enthusiasm that gave rise to new ideas, and motivated us to work will full interest. He has been a major source of inspiration throughout the project as he has not only guided us through the project but also encouraged us to solve the problems that arose during this project. Without him, the project would not have been successful.

Special thanks to Associate Professor Farooq Ahmed Bhatti from Faculty of Electrical Engineering, Military College of Signals, NUST, who has worked brilliantly in the field of Microwave Antennas and we received enough guidance through his practical experience.

We would also like to thank our family members, friends, class fellows and faculty members for their invaluable suggestions and critical review of our project. Their support is commendable

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CHAPTER 1

INTRODUCTION

The purpose of our project is to increase the capacity and coverage in broadband data communication according to the IEEE 802.16e WiMAX standard, an intelligent base station antenna with beam- and null steering over a full circle is developed and optimized.

In this report a circular antenna array of 8 vertical dipoles with a feeding network is described, which provides m beams simultaneously in m directions for m subscribers with a full coverage of 360° around the base station. By means of optimization techniques it is either possible to provide a null without ambiguity in every direction, or to optimize the side lobe attenuation by calculating the amplitudes and phases of every antenna of the array. With this, detection finding or location based services are also possible.

In this report design and implementation of microwave beam former is also presented. It can steer beam in 45^{o} sector in broadside direction of beam former. It consists of eight dipole antennas designed at 2.4 GHz frequency. Each antenna is connected to phase shifter. This phase shifter is controlled by simple control circuitry .The design was with the design of dipole antenna at 2.4 GHz with maximum gain and minimum losses. Agilent ADS software was used as a design tool. The design consists of eight dipole antennas with phase shifter after each antenna and Wilkinson combiners connected the elements. Finally a complete beam former was designed with sufficient good gain. Phase shift is controlled through different voltage level. The control circuitry designed takes the desired direction of beam as an input and after calculating required phase shift for each antenna element, gives different voltage levels asoutput. The complete design has an area of 13cm x 10cm. The reflection coefficient and resonant frequency of the antenna wastested with Vector Network Analyzer. The radiation pattern was checked in anechoic chamber at different angles. The motivation of this thesis is to practically implement a complete antenna structure capable of Beam forming.

1.1 PROJECT OUTLINE

The proposed project proceeds on following fronts:

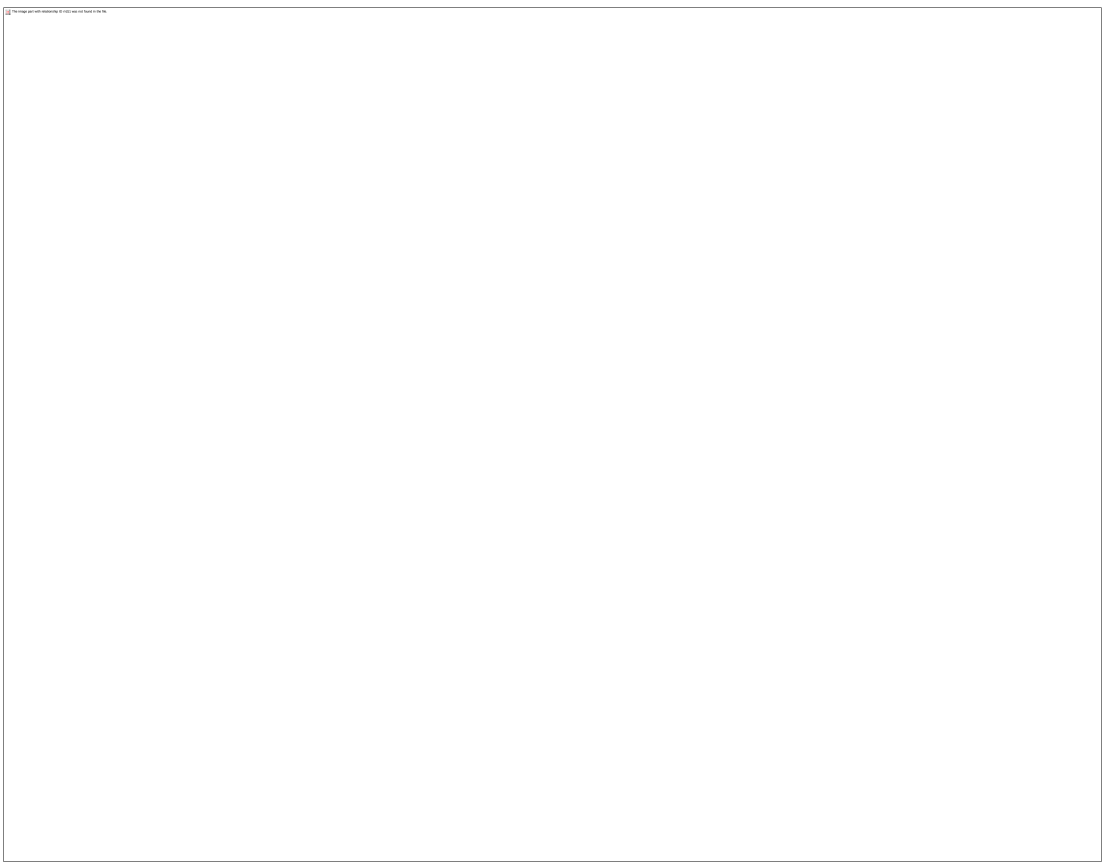


Figure 1.1 Work Flow of the project

CHAPTER 2

LITERATURE REVIEW

This chapter states the background study, motivation and need of the product developed as a result of this research. The detailed objectives and the thesis outline are also presented to give an overview of the project.

2.1 ANTENNA AND ITS BASIC STRUCTURE

An **antenna** (or **aerial**) is an electrical device which converts electric currents into radio waves, and vice versa. It is usually used with a radio transmitter or radio receiver. In transmission, a radio transmitter applies an oscillating radio frequency electric current to the antenna's terminals, and the antenna radiates the energy from the current as electromagnetic waves (radio waves). In reception, an antenna intercepts some of the power of an electromagnetic wave in order to produce a tiny voltage at its terminals, that is applied to a receiver to be amplified. An antenna can be used for both transmitting and receiving.

Antennas are thus essential components of all equipment that uses radio. They are used in systems such as radio broadcasting, broadcast television, two-way radio, communications receivers, radar, cell phones, and satellite communications, as well as other devices such as garage door openers, wireless microphones, Bluetooth enabled devices, wireless computer networks, baby monitors, and RFID tags on merchandise.

Typically an antenna consists of an arrangement of metallic conductors ("elements"), electrically connected (often through a transmission line) to the receiver or transmitter.

An oscillating current of electrons forced through the antenna by a transmitter will create an oscillating magnetic field around the antenna elements, while the charge of the electrons also creates an oscillating electric field along the elements. These time-varying fields radiate away from the antenna into space as a moving electromagnetic field wave. Conversely, during reception, the oscillating electric and magnetic fields of an incoming radio wave exert force on the electrons in the antenna elements, causing them to move, creating oscillating currents in the antenna.

Antennas may also contain reflective or directive elements or surfaces not connected to the transmitter or receiver, such as parasitic elements, parabolic reflectors or horns, which serve to direct the radio waves into a beam or other desired radiation pattern. Antennas can be designed to transmit or receive radio waves in all directions equally (omni-directional antennas), or transmit them in a beam in a particular direction, and receive from that one direction only (directional or high gain antennas).

2.2 IMPORTANT ANTENNA PARAMETERS

DIRECTIVITY OR GAIN:

Directivity is the ratio of the power radiated by an antenna in its direction of maximum radiation to the power radiated by a reference antenna in the same direction. It is measured in dBi (dB referenced to an isotropic antenna) or dB (dB referenced to a half wavelength dipole).

FEED POINT IMPEDANCE:

It is the impedance measured at the input to the antenna. The real part of this impedance is the sum of the radiation and loss resistances. The imaginary part of this impedance represents power temporarily stored by the antenna.

BANDWIDTH:

Bandwidth is the range of frequencies over which one or more antenna parameters stay within a certain range. The most common bandwidth used is the one over which SWR < 2:1.

2.3 ANTENNAS AND FIELDS

RECIPROCITY THEOREM:

An antenna's properties are the same, whether it is used for transmitting or receiving**.**

THE NEAR FIELD

The near field is an electromagnetic field that exists within ~ λ/2 of the antenna. It temporarily stores power and is related to the imaginary term of the input impedance**.**

THE FAR FIELD

An electromagnetic field launched by the antenna that extends throughout all space. This field transports power and is related to the radiation resistance of the antenna.

2.4 DIPOLE ANTENNA BASICS

As the name suggests the dipole antenna consists of two terminals or "poles" into which radio frequency current flows. This current and the associated voltage causes and electromagnetic or radio signal to be radiated. Being more specific, a dipole is generally taken to be an antenna that consists of a resonant length of conductor cut to enable it to be connected to the feeder. For resonance the conductor is an odd number of half wavelengths long. In most cases a single half wavelength is used, although three, five… wavelength antennas are equally valid

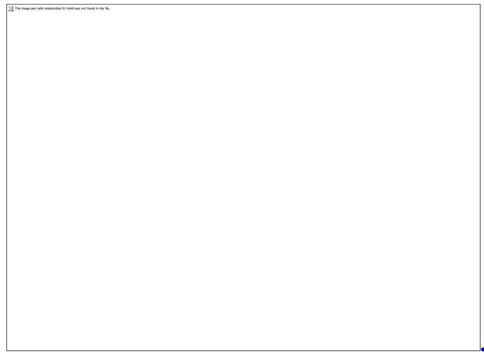


Fig.2.1 The basic half wave dipole antenna

Fig.2.2 Current and voltage distribution of dipole antenna

The current distribution along a dipole is roughly sinusoidal. It falls to zero at the end and is at a maximum in the middle. Conversely the voltage is low at the middle and rises to a maximum at the ends. It is generally fed at the centre, at the point where the current is at a maximum and the voltage a minimum. This provides a low impedance feed point which is convenient to handle. High voltage feed points are far less convenient and more difficult to use. When multiple half wavelength dipoles are used, they are similarly normally fed in the centre. Here again the voltage is at a minimum and the current at a maximum. Theoretically any of the current maximum nodes could be used

2.5 DIPOLE ARRAYS

Dipole arrays are high gain antennas used for analog and digital short wave broadcasting. Antenna consists of an array of half-wave, folded dipoles that are optimized to achieve a wide impedance bandwidth. The dipoles are mounted in front of an reflecting screen of closely spaced horizontal wires that suppresses radiation behind the array. The dipoles are interconnected through a set of balanced transmission lines contained within the antenna. The azimuthally beams of the array can be steered using one or more high power RF switches. This slewing system inserts or deletes delay lines that change the phase relationships between the columns thus shifting the direction of radiation. The switches are motor-driven and controlled by a microprocessor system which can be activated either by a control panel or by the transmitting station's control computer. Slewing takes 3 to 5 seconds.

Dipole arrays have vertical slew capability that permits the broadcaster to change the elevation pattern of the antenna and thus alter the distance the antenna covers. Vertical slew is accomplished in 3 to 5 seconds using motorized RF switches. A single control system operates and monitors the vertical and azimuthally slewing switches.

Dipole arrays typically operate over a frequency range of one octave (2:1 ratio of highest to lowest frequency), which enables the antenna to operate over 4, 5, or even 6.

2.6 DIPOLE WITH BALUNS

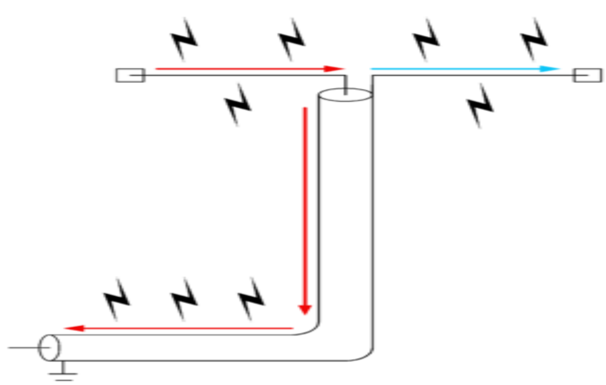


Fig.2.3 Coax and antenna both acting as radiators instead of only the antenna.

A dipole, being composed of two symmetrical ungrounded elements, works best when fed by a balanced transmission line, such as ladder line. When a dipole with an unbalanced feed line such as coaxial cable is used for transmitting, the shield side of the cable, in addition to the antenna, radiates. This can induce RF currents into other electronic equipment near the radiating feed line, causing RF interference. Furthermore, the antenna is not as efficient as it could be because it is radiating closer to the ground and its radiation (and reception) pattern may be distorted asymmetrically. At higher frequencies, where the length of the dipole becomes significantly shorter than the diameter of the feeder coax, this becomes a more significant problem. To prevent this, dipoles fed by coaxial cables have a balun between the cable and the antenna, to convert the unbalanced signal provided by the coax to a balanced symmetrical signal for the antenna. Several types of baluns are commonly used to transmit on a dipole: current baluns and coax baluns.

2.7 CURRENT BALUN

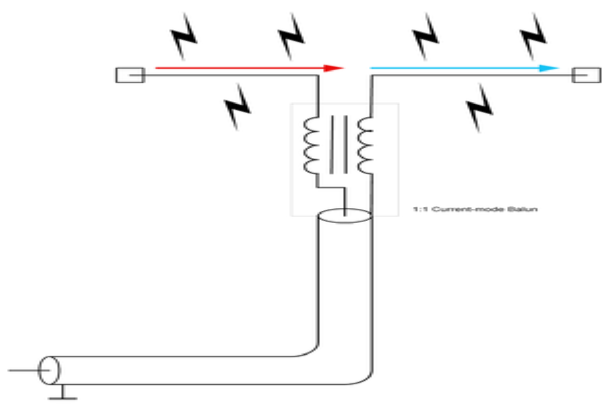


Fig 2.4 Dipole with a current balun.

A current balun is a bit more expensive but has the characteristic of being more broadband. It can also be as simple as winding the coax cable over a ferrite core. Or nothing but coax cable;p p nlkjk80-

2.8 Coax balun

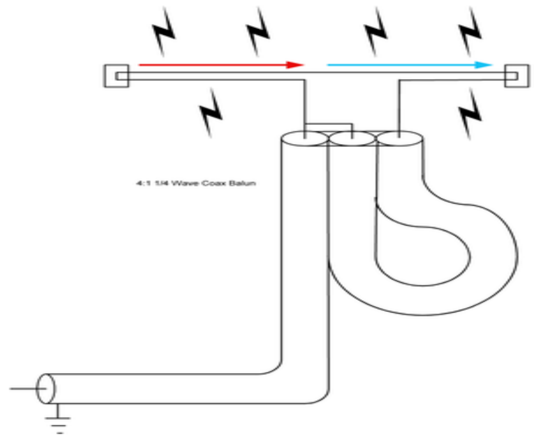


Fig 2.5 A folded dipole (300Ω) to coax (75Ω) 4:1 balun.

A coax balun is a cost effective method to eliminate feeder radiation, but is limited to a narrow set of operating frequencies.One easy way to make a balun is a (λ/2) length of coaxial cable. The inner core of the cable is linked at each end to one of the balanced connections for a feeder or dipole. One of these terminals should be connected to the inner core of the coaxial feeder. All three braids should be connected together. This then forms a 4:1 balun which works correctly at only a narrow band of frequencies.

2.9 SLEEVE BALUN

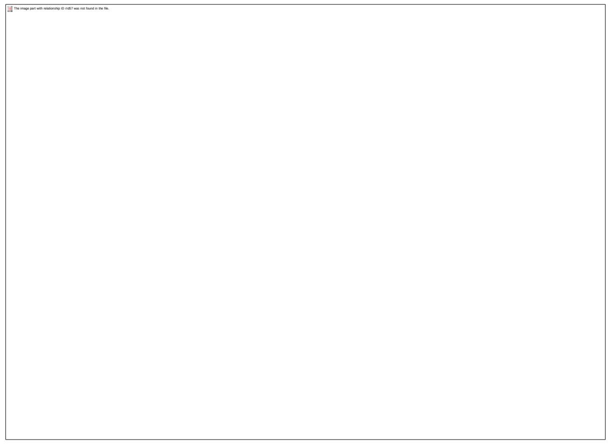


Fig 2.6 Dipole using a sleeve balun.

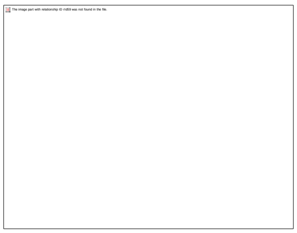
At VHF frequencies, a sleeve balun can also be built to remove feeder radiation.

Another narrow band design is to use a λ/4 length of metal pipe. The coaxial cable is placed inside the pipe; at one end the braid is wired to the pipe while at the other end no connection is made to the pipe. The balanced end of this balun is at the end where the pipe is wired to the braid. The λ/4 conductor acts as a transformer converting the infinite impedance at the unconnected end into a zero impedance at the end connected to the braid. Hence any current entering the balun through the connection, which goes to the braid at the end with the connection to the pipe, will flow into the pipe. This balun design is impractical for low frequencies because of the long length of pipe that will be needed.

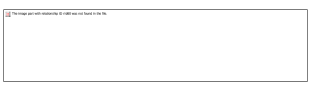
2.10 ANTENNA ARRAYS PRINCIPLES AND PROPERTIES

Antenna arrays are formed by assembling identical (in most cases) radiating elements such as dipoles for example. In the diagram below is shown an Antenna array with its elements along the z axis such that the distance between each two successive elements is equal to d.

Antenna arrays are characterized by their array factor which is given by the formula



where



N the number of elements making the array, k = 2Pi / wavelength, is the polar angle and β is the difference of phase between any two successive elements forming the array.

2.11 COMMON ANTENNAS AND THEIR PATTERNS

In this section, some common antennas are described along with details about typical patterns that can be expected from these common antennas. Described here are a dipole, a collinear array, a single patch antenna, a patch array, a Yagi and even a sector antenna. The patterns from each antenna are shown and explained in detail, including a 3D radiation pattern. The emphasis is on describing the patterns and the parameters that are derived from these patterns.

It is important to mention that it doesn't really matter in which direction the patterns are shown. The orientation of a particular pattern is often a matter of personal preference. For example, some people like directional antenna patterns to always point up while others like them to point to the right or left because that's the way the antenna will often be deployed. The important thing is to have some basic knowledge of what these antennas are meant to do, so that you can understand the pattern parameters. Then the pattern's direction is of little importance.

OMNIDIRECTIONAL ANTENNAS

Omnidirectional antennas are commonly referred to as "omnis." In addition, an omni often refers to an omnidirectional antenna but specifically not a dipole. Often, an omni refers to an omnidirectional antenna that has more gain than a dipole. However, a dipole is an omnidirectional antenna as we will see in the next section. The dipole is just a special case.

DIPOLE ANTENNAS

A dipole antenna most commonly refers to a half-wavelength ($\lambda/2$) dipole. The physical antenna (not the package that it is in) is constructed of conductive elements whose combined length is about half of a wavelength at its intended frequency of operation. This is a simple antenna that radiates its energy out toward the horizon (perpendicular to the antenna). The patterns shown in Figure are those resulting from a perfect dipole formed with two thin wires oriented vertically along the z-axis.

The resulting 3D pattern looks kind of like a donut or a bagel with the antenna sitting in the hole and radiating energy outward. The strongest energy is radiated outward, perpendicular to the antenna in the x-y plane.

The azimuth plane pattern is formed by slicing through the 3D pattern in the horizontal plane, the x-y plane in this case, just as you would slice through a bagel. Notice that the azimuth plane pattern is non-directional, that is, the antenna radiates its energy equally in all directions in the azimuth plane.

Fig2.7Dipole Antenna with 3DRadiation Pattern, Azimuth Plane Pattern&Elevation Plane Pattern

COLLINEAR OMNI ANTENNAS

In order to create an omnidirectional antenna with higher gain, multiple omnidirectional structures (either wires or elements on a circuit board) can be arranged in a vertical, linear fashion to retain the same omnidirectional pattern in the azimuth plane but a more focused elevation plane beam which then has higher gain. This is frequently referred to as a *collinear array*. Note that the higher gain doesn't imply that the antenna creates more power. It means that the same amount of power is radiated in a more focused way.

A typical omni pattern is shown in Figure 5. The antenna shown in the figure was formed from an array of three dipoles, oriented along the z-axis. Notice now that the 3D pattern shown in Figure 5a looks like a flatter "bagel" with a little "bowl" stuck to the top and bottom. The bagel forms the omnidirectional azimuth plane shown in Figure 5b and the main lobes in the elevation plane, just like the dipole. The little "bowls" on the top and bottom form the sidelobes present in the elevation plane in Figure 2.8.

Again, the azimuth plane pattern is formed by slicing the 3D pattern through the horizontal plane (the x-y plane). As expected, the pattern is circular and it passes through the peak gain at all angles. Note that the pattern in the orthogonal planes is directional, so this antenna meets the basic definition of an omnidirectional antenna.

As is typical of higher gain omnidirectional antennas, the elevation plane shows obvious side lobes. The side lobes in the principal plane patterns are formed by slicing through the "bowls" that sit above and below the main lobes in the 3D pattern. These lobes are about 14 dB down from the peak of the main lobes. Note that the azimuth plane pattern is still the same well-behaved, circular pattern as in the dipole, but the elevation plane pattern is much narrower, indicating that the power is radiated in a more directed way, thus producing a higher gain.

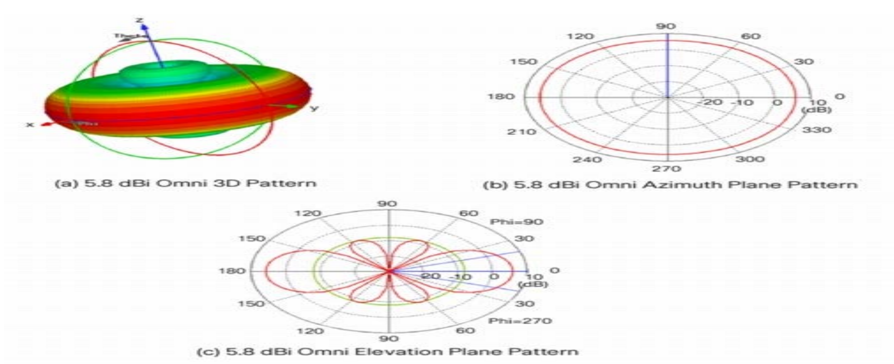


Figure2.8 3D Radiation Pattern , Azimuth Plane Pattern and Elevation Plane Pattern

As shown in Figures 2.7 and 2.8, the goal of a dipole or any omni is to radiate energy equally in all directions in a plane. For dipoles and collinear arrays, the omni-directional plane is intended to be the azimuth plane (the plane of the floor or the ground). For this reason, it doesn't matter how the patterns are presented. It is understood that the elevation plane pattern is always orthogonal to the azimuth plane pattern. The orientation of the actual plot is largely dependent on the orientation of the antenna in the measurement system and that's all there is to it. So, whether the elevation plane looks like Figure 2.9, you can be certain that when your dipole or omni is oriented vertically, the antenna will radiate out toward the horizon in an omnidirectional fashion.

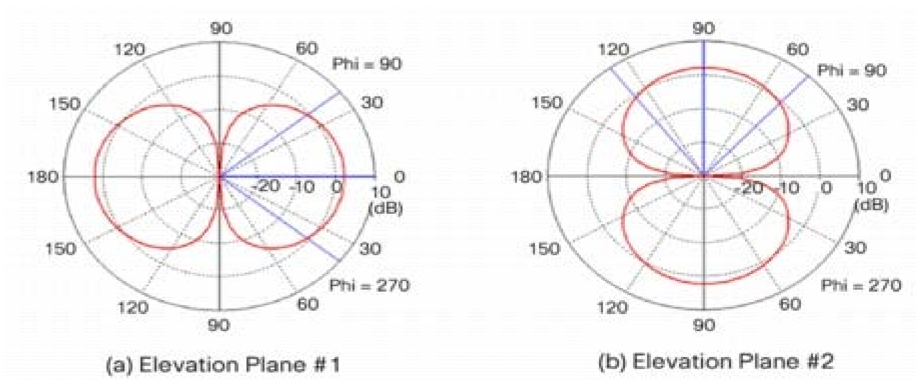


Figure 2.9 Elevation Plane Demonstration2.1 Smart Antenna

Many refer to smart antenna systems as smart antennas, but in reality antennas by themselves are not smart.It is the digital signal processingcapability, along with the antennas, which make the system smart. A smart antenna system comprises of an antenna capable of Beam-forming and Digital Signal Processing at the backend which is actually an algorithm for Direction of Arrival (DOA) estimation [1]. Electrical smart antenna consists of two or more antennas, a digital signal processorBased on the time delays due to the impinging signals onto the antenna elements. The digital signal processor computes the direction-of-arrival (DOA) of the signal-of-interest (SOI). Then it adjusts the excitations (gains and phases of the signals) to produce a radiation pattern that focuses on the SOI while tuning out any interferers or signals-not-of-interest (SNOI) i.e.Beam-forming.

2.12 BEAMFORMING

Beam-forming is a signal processing technique used in sensor arrays for directional signal transmission or reception. This is achieved by combining elements in the array in such a way that signals at particular angle experience constructive interference while others experience destructive interference. Beam forming can be used at both the transmitter and receiver side to achieve spatial selectivity. The improvement compared with an Omni-directional reception/transmission is known as the receive/transmit gain.

Beam forming can be used for both radio and sound waves. It has found numerous applications in radar, sonar, seismology, wireless communication, radio astronomy, acoustics and biomedicine. Adaptive Beam forming is used to detect an estimate of the signal of interest at the output of a sensor array by means of data adaptive spatial filtering and interference rejection.

BEAM FORMING TECHNIQUES

Deploying beamforming in commercial wireless applications demands reduction in implementation cost and complexity. The following techniques are some of the Beam forming techniques.

a) Digital Beam forming (DBF)

b) Spatially Multiplexing of Local Elements (SMILE)

c) Hybrid analog DBF

d) Microwave Beam forming (MBF)

Digital beamforming (DBF) allows using sophisticated signal processing operations on the array signals. However, one full receiver including RF down-conversion, low-pass filter (LPF), and analog-to-digital converter (ADC) should be used after each antenna element, which makes this structure very complex and costly. In addition, multiple signals are transferred to the processor in parallel which limits the data throughput due to the speed bottleneck limitation of the current digital signal processor (DSP) technology.

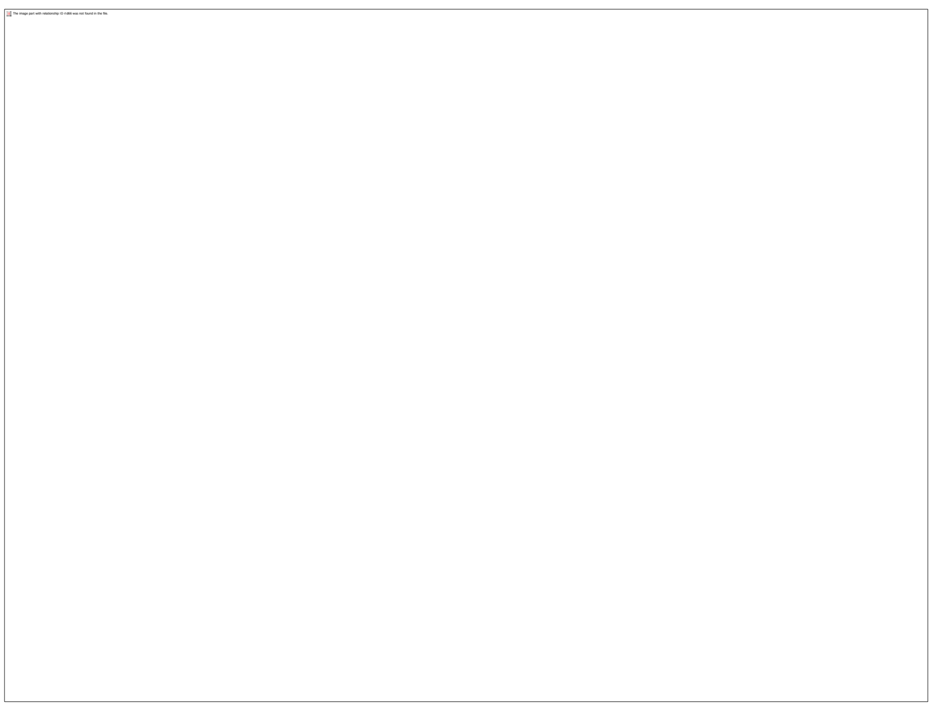


Figure 2.10 Digital Beamforming Block Diagram

The technique of spatially multiplexing of local elements (SMILE)**,** in which the antenna array signals are transferred to the processor sequentially in time multiplex fashion to implement beamforming in the digital domain. This technique uses one RF down conversion branch to lower the complexity. Hybrid analog-DBFis a technique in which Beam forming is performed in the analog IF domain to overcome the speed bottleneck of the processor.

Microwave beamforming (MBF) is an attractive alternative due to using one RF down-conversion and ADC branches. Moreover, because only one signal is transferred to the processor higher throughput is possible. On the other hand, having a single receiver in the MBF structure limits its signal processing capability.

2.13 CRITERIA FOR SELECTION OF ANTENNA

Differentantenna structures for wireless communication have been proposed in the literature.These structures are motivated by their low profile, low cost, and easy fabrication. Also, monopole antennas have been used in wireless communications because of their wide-band characteristics and design simplicity [4]. The first step in designing of the model was to select the type of antenna. The available options are:

a) Array Antenna - directional

b) Microstrip Technology - low profile

c) Aperture Antenna - microwave frequencies

d) Reflector Antenna - long ranges

Our selection criteria is based on the following aspects

a) Cost

b) Directional

c) Compact

d) Miniaturization

e) State of the Art Technology

After much thought and consideration, it was decided to use the microstrip technology for this Beam-forming antenna as it has most of the features that fulfilled the requirements such as:

a) Used in mobile phones

b) Directional Antenna

c) Medium Directivity

d) Lightweight

e) Compactness

2.14 TYPES OF PHASE SHIFTERS

SWITCHED-LINE PHASE SHIFTER

In these phase shifters two SPDT switches are used to switch two line lengths, one of which is X degrees longer in electrical length than the other. A typical circuit is shown in Figure 2.11.

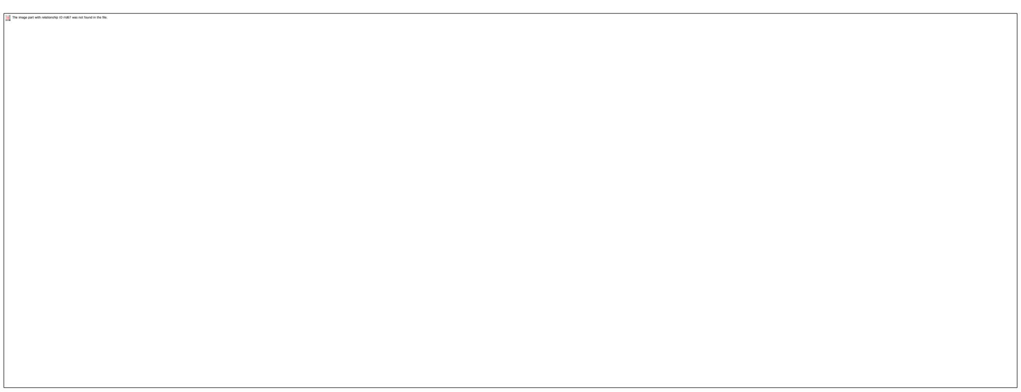


Figure 2.11 Typical Switched Line Phase Shifter

It is important to choose a switch technology appropriately for the frequency band of interest.Switched-line phase shifters are often used for the two largest phase bits of a multi-bit phase shifter (180 and 90 degrees).

LOADED-LINE PHASE SHIFTER

For phase shifts of <45 degrees, loaded-line phase shifters as shown in Figure 2.3 can be used.These phase shifters work by adding a shunt reactance to the micro-strip line (in the form of an inductor or capacitor) causing the incident signal to undergo a phase shift.

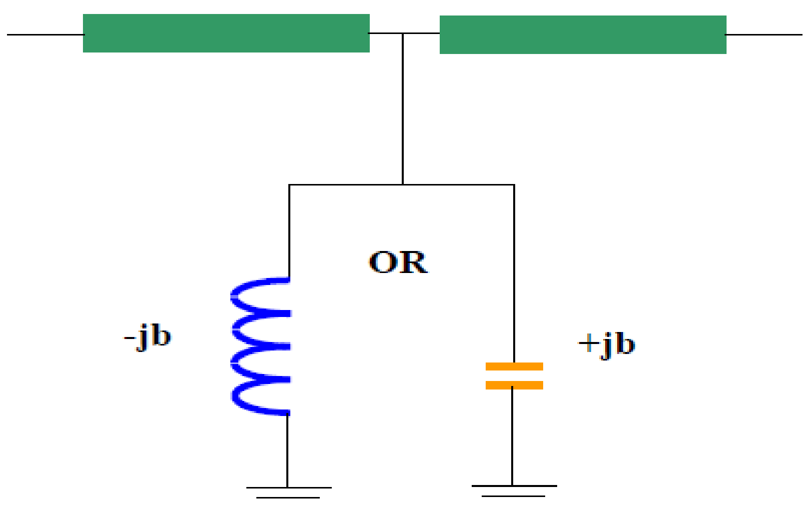


Figure 2.12 ALoaded-line phase shifter

The disadvantage of these phase shifters, are that in order to large values of phase shift, high values of b are required thus increasing the insertion loss.

HIGH-PASS/LOW-PASS PHASE SHIFTER

It is such a type of phase shifter in which one arm forms a high-pass filter while the opposite arm forms a low-pass filter. It can provide near constant phase shift over an octave or more. A second advantage of the high-pass/low-pass phase shifter is that it offers a very compact layout because lumped elements are typically used instead of delay lines.

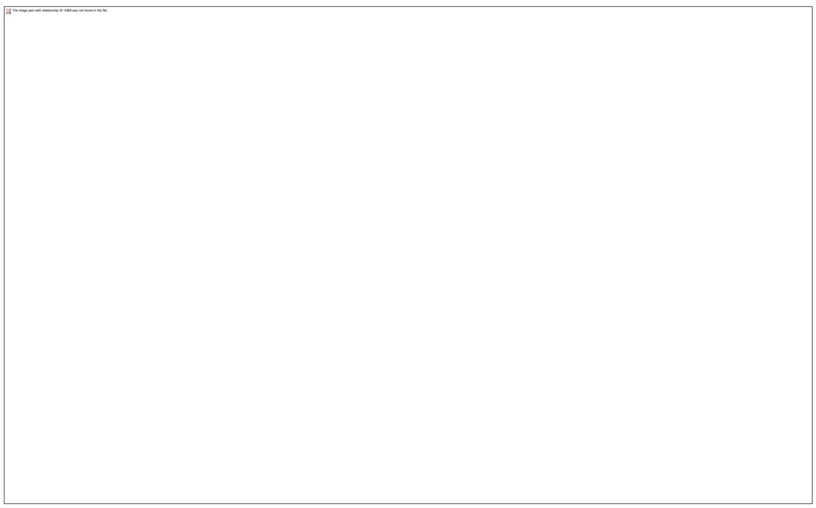


Figure 2.13 A High pass/low pass Phase Shifter

REFLECTION TYPE PHASE SHIFTER

Reflection phase shifters work by having switchable terminations which create switchable reflection coefficients. The main type of reflection phase shifter uses switched line lengths either by using a PIN switch or by a variable reactance (e.g.varactor) to alter electrical length. In both cases the signal incurs twice the extra electrical length as the signal is reflected back.

The phase shifter in this project is a reflection type phase shifter which uses the varactor diode.

CHAPTER 3

ANTENNA DESIGN

Conventional base station antennas in existing operational systems are either Omnidirectional or sectorized. The greater part of the transmitted signal power is radiated into directions other than toward the specific user. This causes interference, reduces efficiency and the range of coverage. Especially in new broadband services as WiMAX, where the user front-end is very simple, it becomes necessary to provide every user with a specific beam offering enough gain to increase the range. It is also important to reduce interference by other users or services by means of beam forming in a way, that either the side lobe attenuation of the base station antenna array as a whole is optimized or by null steering. In rural areas a whole 360° degrees coverage around the base station is desired. This leads to the solution introduced here of circular antenna arrays, a setup which can also be used for direction finding. The antenna array consists of n vertical dipoles equally spaced on a ring with diameter d (fig.3.1). This building block is vertically stacked many times to achieve enough gain in the horizontal plane.

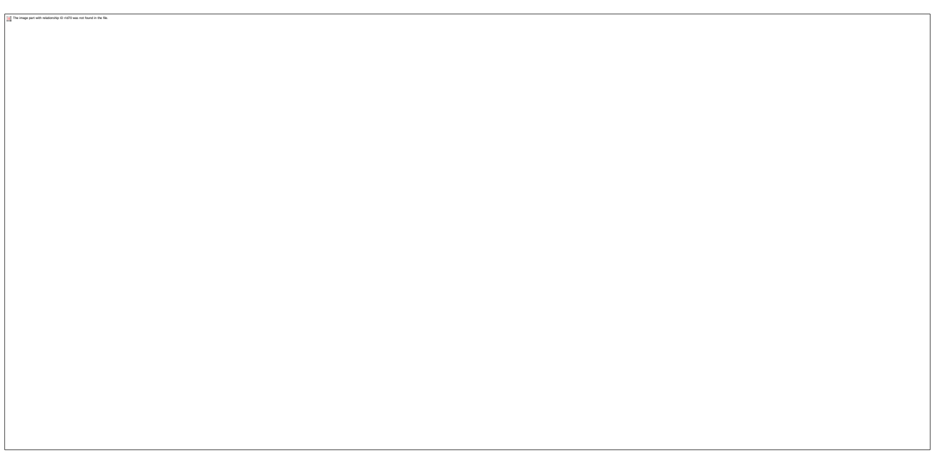


Fig. 3.1

The antenna array under consideration consists of 8 vertical dipoles, equally spaced on a circle with diameter d, according to Fig. 1. A power-combiner/ divider network is connected to the feed point of every dipole with m inputs/outputs according to the number of wanted coinstantaneous beams or null directions. For each independent beam direction the weights of the amplitudes and phases have to be calculated and optimized. The adjustment can be performed directly by phase shifters and attenuators in the RF-region or after linear down-conversion and analog to digital conversion by a DSP.

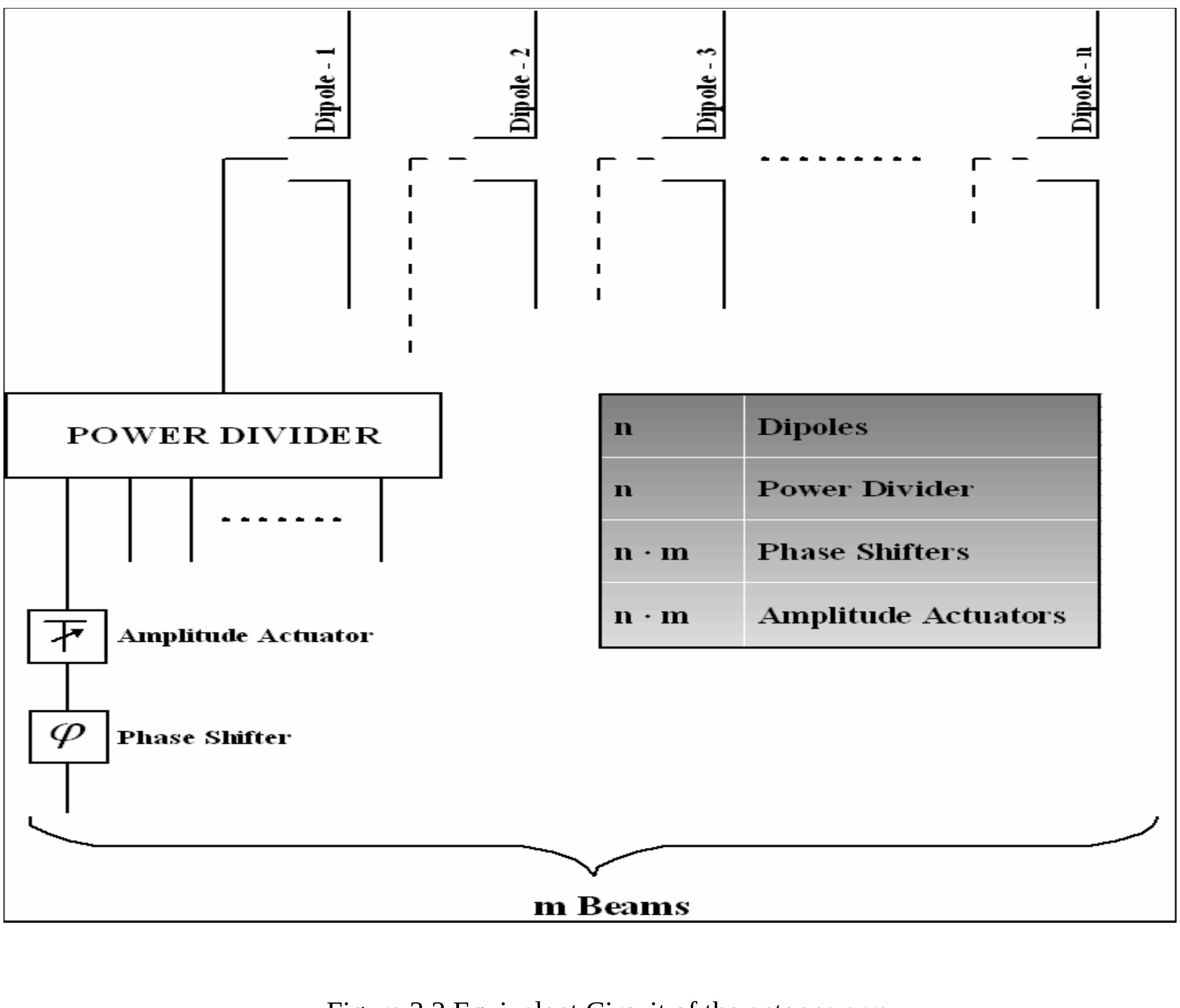


Figure 3.2 Equivalent Circuit of the antenna array

The analysis of the structure is done by FEKO, a field simulation programme using the Method of Moments and additional hybrid methods. The numerical calculations and the optimization process can be vastly accelerated using impressed currents similar to a Hertzian dipole, but omitting its infinitesimal length. With impressed currents (infinite generator impedance) there is no mutual coupling and the analysis is very fast.

To consider mutual coupling a simple procedure has been found that uses a coupling impedance matrix $\|Z\|$. From given currents (magnitude and phase) for each beam direction the generator voltages (magnitude and phase) can be calculated using $\|Z\|$ and equation (1).

$$\bar{U}_0 = \begin{pmatrix} U_{01} \\ U_{02} \\ \cdots \\ U_{0N} \end{pmatrix} = \|Y\|^{-1} \cdot \bar{I} = \|Z\| \cdot \begin{pmatrix} I_1 \\ I_2 \\ \cdots \\ I_N \end{pmatrix} \quad (1)$$

$\|Z\|$ remains the same for all scanning directions and thus has to be determined only once.

Optimal Geometry

The ratio of the array-parameter and the wavelength d/λ is crucial for optimal results. For d « λ the antenna characteristic of the whole array is not different from the pattern of a single dipole. The horizontal pattern is a circle; with an increasing ratio d/λ the gain of the array increases also. For d/λ > 1 the side lobe level is growing at the cost of the main lobe. With increasing d/λ the number of side lobes (and nulls) and the energy radiating into unwanted directions are increasing. The optimum region for obtaining maximum gain, high side lobe attenuation and/or an unambiguous null is

$$\frac{1}{2} \le \frac{d}{\lambda} \le \frac{3}{2} \quad (2)$$

Within this region it is possible to adjust every azimuth angle of the beam with a side lobe attenuation better than 22 dB and/or to provide an unambiguous null by using the optimizer OPTFFEKO.

ROTATION OF THE BEAM IN AZIMUTH AND ELEVATION

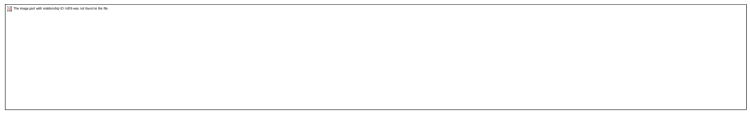
For any wanted beam direction around the base station we derived a formula for the phase of the feed current of every dipole. To achieve a planar wave front in the direction of the user the relationships in Figure 3.3 are valid.

Fig.3.3 Planar wave front

To maintain a main lobe in the direction φ_{max} with $0 < \varphi_{max} < 360°$, the phase Ψ of every dipole has to be adjusted according to:

$$\Psi_{\nu} = -\frac{2\pi}{\lambda} R \cdot \cos\left(\varphi_{\nu} - \varphi_{\max}\right) \quad (3).$$

Where ν is indicating dipole ν, φ_ν his angle position on the circle and φ_{max} the direction of the user. By adding a $\sin(\vartheta)$-term it is also possible to adjust the elevation angle of the main lobe within certain limits due to the characteristics of the single dipole.



where max ϕ and max ϑ points in the direction of the desired direction.

With this analytical formula every azimuth angle of the main lobe is tuneable, the side lobe attenuation reaches values up to 12 dB. In Figure 4 the antenna pattern is shown for 3 different user directions.

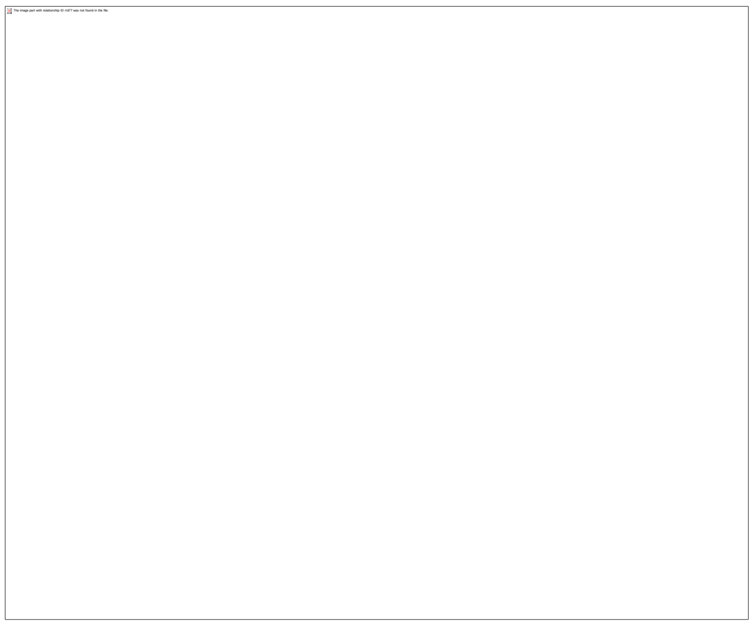


Fig.3.4 Examples of Beam steering

The form of the antenna characteristic remains nearly the same with a gain of 7.5 dB and a side lobe attenuation of 12 dB.

CHAPTER 4

8 DIPOLE ARRAY

The antenna array under consideration consists of 8 vertical dipoles, equally spaced on a circle with diameter d, according to Fig. 1. A power-combiner/ divider network is connected to the feed point of every dipole with m inputs/outputs according to the number of wanted coinstantaneous beams or null directions. For each independent beam direction the weights of the amplitudes and phases have to be calculated and optimized. The adjustment can be performed directly by phase shifters and attenuators in the RF-region or after linear down-conversion and analog to digital conversion by a DS.

Fig 4.1 8 Dipole array antenna

4.1 FABRICATION OF SINGLE DIPOLE

Single dipole antenna fabrication is the first step towards the 8 arrays fabrication.fig shows the simple construction of single dipole antenna using RG 58 cable, SMA Conector, balun for impedance matching and simple copper wire.

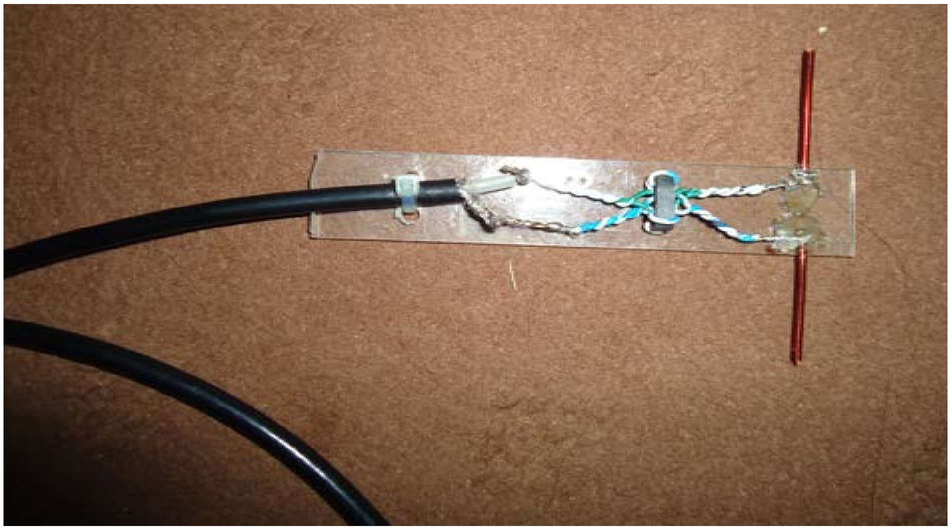


Fig. 4.2 Half wave dipole antenna

HFSS SIMULATION RESULTS OF SINGLE DIPOLE

RETURN LOSS

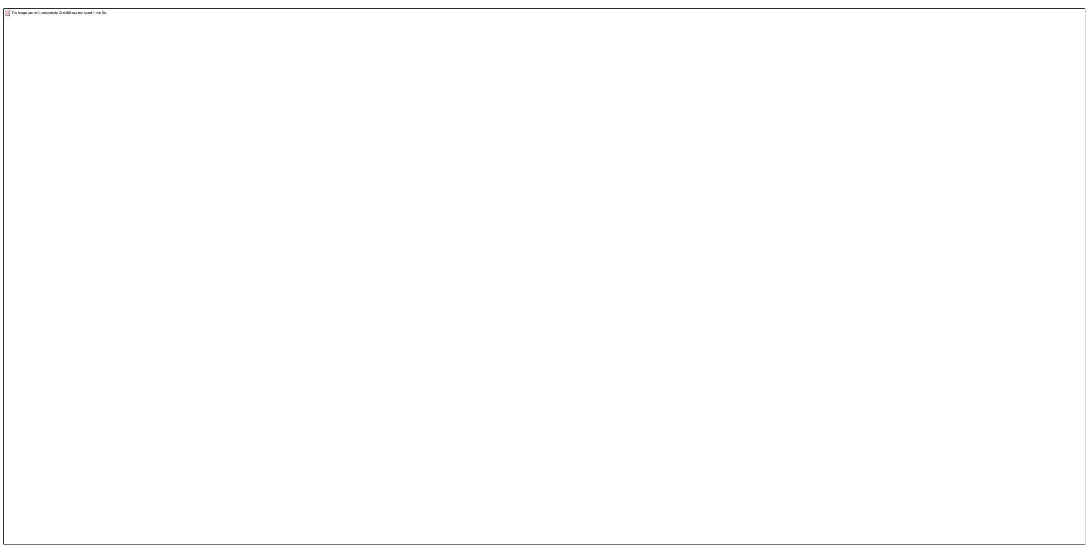


Fig 4.3 Achieved return loss at 2.4 GHz

INPUT IMPEDENCE

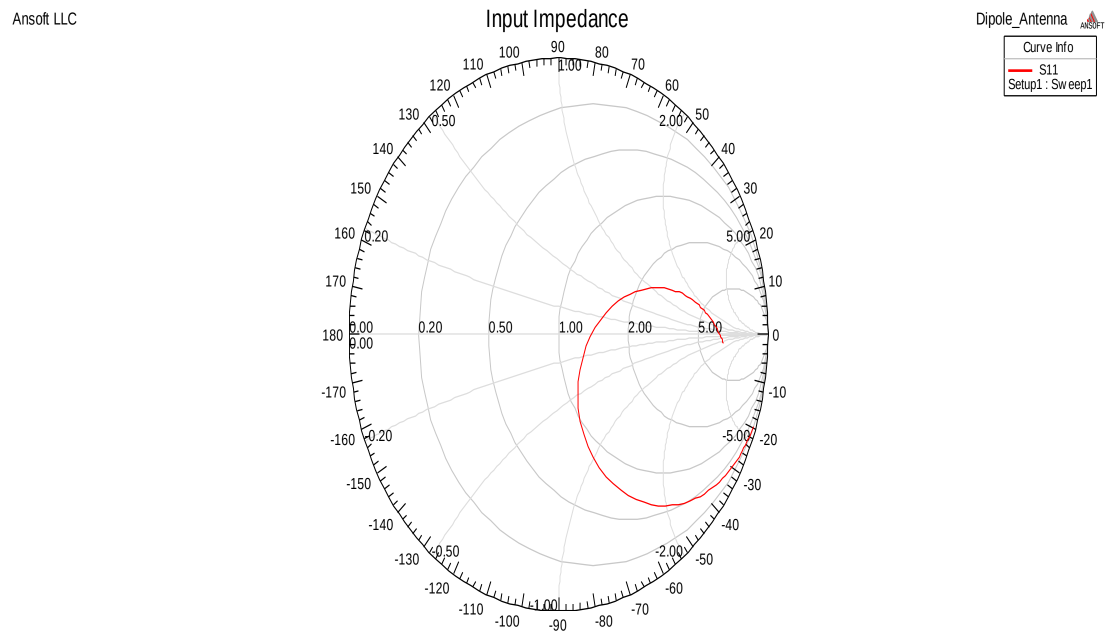


Fig 4.4 Input impedance of half wave dipole antenna at 2.4 GHz

ANTENNA GAIN

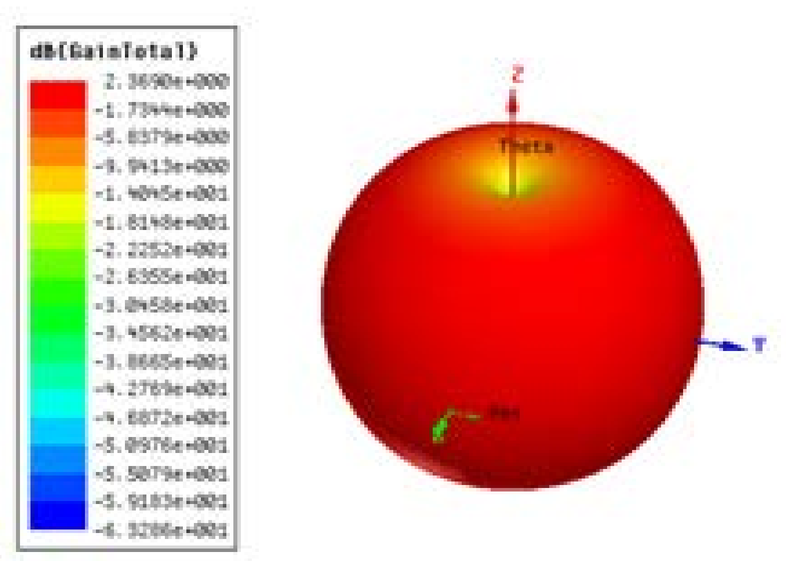


Fig 4.5 3D gain plot of half wave dipole antenna.

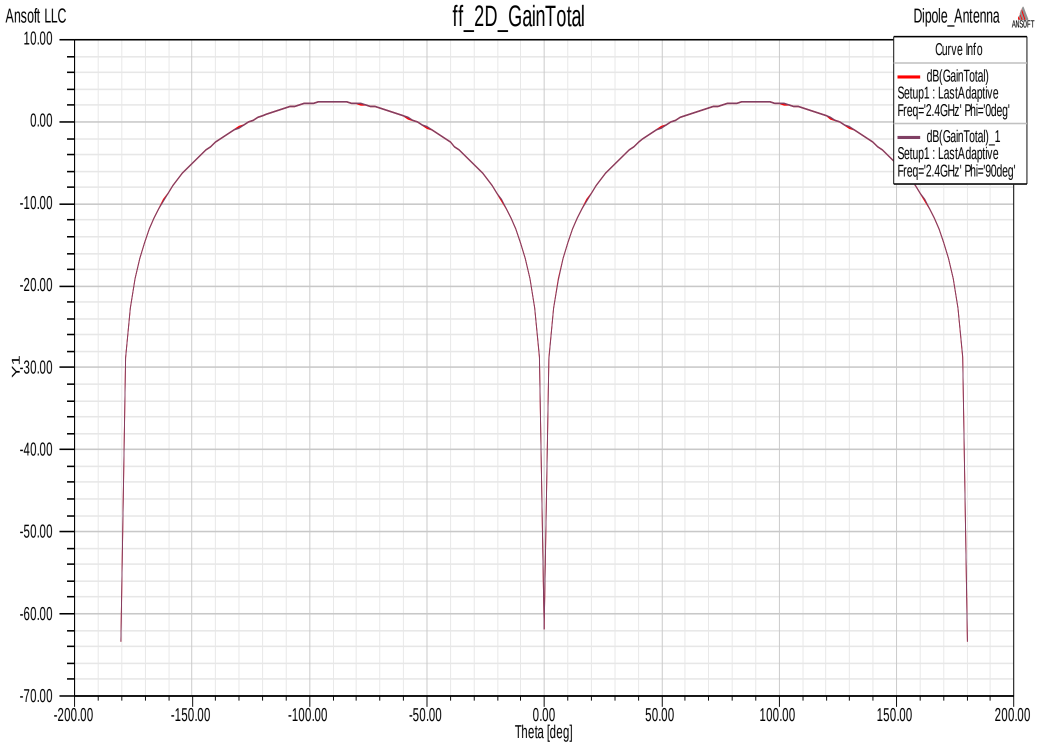


Fig 4.6 2D gain plot of half wave dipole antenna.

VNA MEASURED RESULTS

Fig 4.7 measured results of dipole antenna on VNA.

4.2 8 DIPOLE ARRAY

8 dipole array is constructed with help of 8 single dipole circularly placed with diameter of 19 cm on simple glass plate mounted on a circular frame of plastic material as show in the below figure.

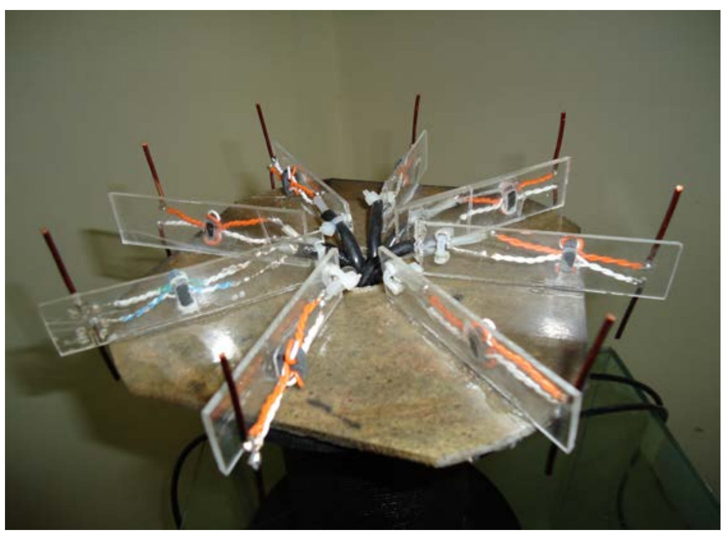


Fig 4.8 fabricated 8 dipole array antenna.

HFSS SIMULATION RESULTS OF 8 ARRAY DIPOLE

HFSS DESIGN

Fig 4.9 HFSS design of 8 dipole array

DESIGN PARAMETERS

Fig 4.10 design parameters of 8 dipole array.

3D GAIN PLOT OF 8 DIPOLE ARRAY

Fig 4.11 3D gain plot of phase shifted 8 dipole antenna array.

2D GAIN PLOT OF 8 DIPOLE ARRAY

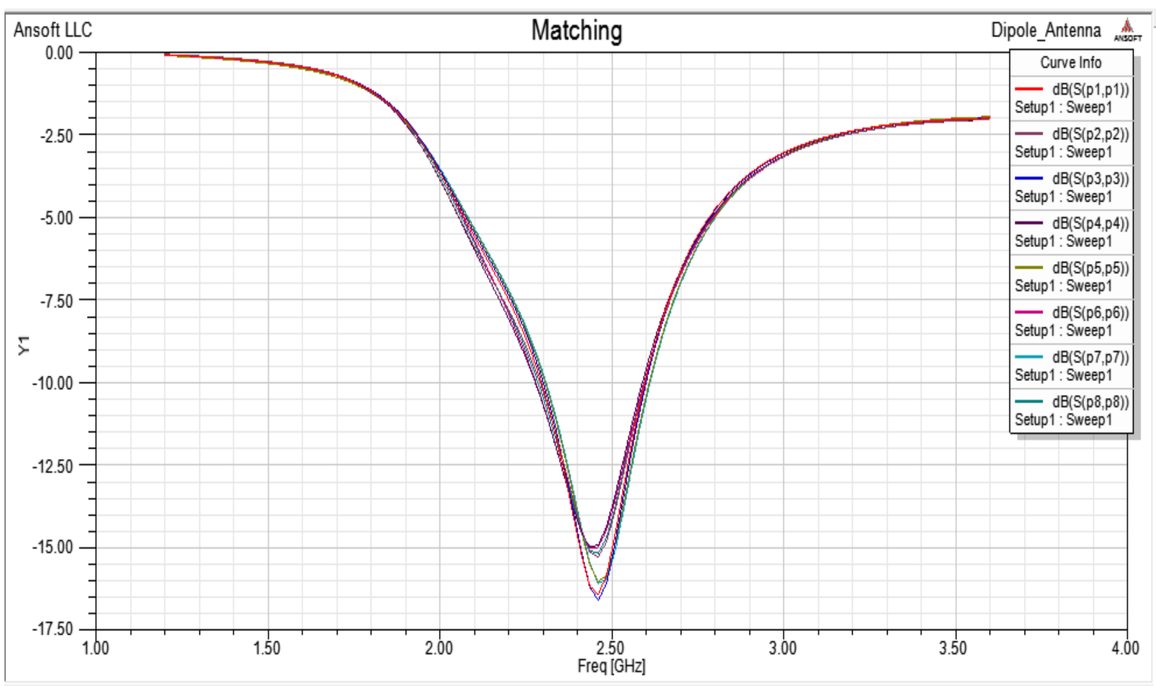


Fig 4.12 2D gain plot of dipole antenna array.

4.3 COMPONENTS USED IN DIPOLE ANTENNA

SMA CONNECTOR

SMA (Sub Miniature version A) connectors are coaxial RF connectors developed in the 1960s as a minimal connector interface for coaxial cable with a screw type coupling mechanism. The connector has 50 Ω impedance. It offers excellent electrical performance from DC to 17 GHz. The SMA connector consists of a 1/4"-36 threads. The male is equipped with a 0.312" (7.925 mm) hex nut.

In SMA and RP-SMA connectors, the terms "male" and "female" refer exclusively to the male center pin and its female sleeve counterpart rather than to the threads that are used to hold the connection in place. The male connector has inside threads while the female connector has outside threads.

The SMA connector uses a polytetrafluoroethylene (PTFE) dielectric which will contact along the mating plane. Variability in the construction and the mating of the connectors limit the repeatability of the connector impedance. For that reason, an SMA connector is not a good choice for metrological applications.

SMA connectors are rated for 500 mating cycles, but to achieve this it is necessary to properly torque the connector when making the connection. A 5/16 inch torque wrench is required for this, set to 3–5 in·lbf (0.3 to 0.6 N·m) for brass, and 7–10 in·lbf (0.8 to 1.1 N·m) for stainless steel connectors. Flats are sometimes also provided on the cable side of the connector assembly so that a second wrench can be used to prevent it from rotating and damaging the joint to the cable. It is also advisable to clean out loose debris from the internal surfaces with compressed air or a gas duster can before mating

RG 58 CABLE

RG-58/U is a type of coaxial cable often used for low-power signal and RF connections. The cable has a characteristic impedance of either 50 or 52 Ω. "RG" was originally a unit indicator for bulk RF cable in the U.S. military's Joint Electronics Type Designation System. There are several versions covering the differences in core material (solid or braided wire) and shield (70% to 95% coverage).

The outside diameter of RG-58 is around 0.2 inches (5 mm). Plain RG-58 cable has a solid center conductor. The RG-58A/U features a flexible 7 or 19 strand center conductor.

Most two-way radio communication systems, such as marine, CB radio, amateur, police, fire, WLAN antennas etc., are designed to work with a 50 Ω cable.

RG-58 cable is often used as a generic carrier of signals in laboratories, combined with BNC connectors that are common on test and measurement equipment such as oscilloscopes.

RG-58 in versions RG-58A/U or RG-58C/U was once widely used in "thin" Ethernet (10BASE2), where it provides a maximum segment length of 185 meters. However, it has been almost completely replaced by twisted pair cabling such as category 5 and similar cable in data networking applications.

RG-58 cable can be used for moderately high frequencies. Its signal attenuation depends on the frequency, e.g. from 0.11 dB/m at 50 MHz to 1.4 dB/m at 2 GHz.

BALUN

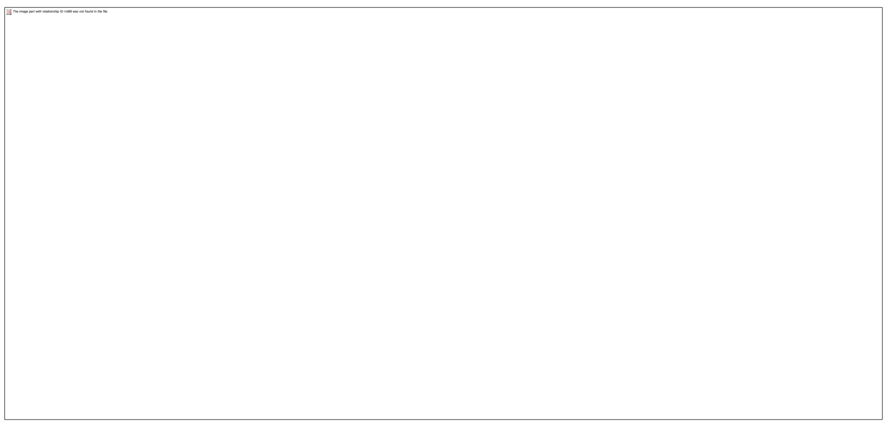
A **Balun** is used to "balance" unbalanced systems - i.e. those where power flows from an unbalanced line to a balanced line (hence, balun derives from *bal*ance to *un*balanced)
The alternative arrangement I used was to combine the impedance transformation and balun functions into a 1:4 Guanella current balun mounted in the terminal box. This allows single-wire elements to be used, which simplifies assembly and tuning. The 1:4 balun comprises two 1:1 baluns wound with 8 turns of coax on a FT 140-61 ferrite toroid; the two baluns are then connected in series at the 50 ohm feedline end, and in parallel at the antenna end. The coax needs to have a characteristic impedance of 25 ohms -

something which is not easily available; so each balun is actually wound with two 50 ohm coaxes which are connected in parallel at each end - inner to inner, braid to braid.

BALUN CONSTRUCTION:

Cut two 510mm lengths of RG316 miniature coax (or RG174 if you do not intend running more than 100W). Trim the four ends to form short pigtails. Lay the two coaxes alongside one another and connect centre-to centre and braid-to-braid at each end. Although not strictly necessary, I find it helps keep things neat if you slide a few narrow pieces of heat-shrink tubing over the coaxes to keep them together. You have now created a single transmission line with a Characteristic Impedance of 25 Ohms. Now wind 8 turns of this twin cable onto a FT140-61 toroid to form a 1:1 Choke. The “crossover” winding is not an electrical requirement - it's just an easy way to get the coaxes to emerge at opposite ends of the ferrite core. Use a couple of plastic tie-wraps to hold the coax to the core at each end.

Now bind the two 1:1 chokes together - again, I used a couple of plastic tie-wraps. Ensure that the two Chokes are aligned - i.e. the coaxes emerge at roughly the same positions. At one end of the assembly (left side of the 'photo) connect the coaxes in parallel: braid-to-braid, inner-to-inner; this is the end which connects to the antenna elements. At the other end of the assembly (right side of the 'photo) connect the coaxes in series: braid from one Choke to inner of the other; this is the end which connects to the SO239 and the feedline, using the remaining braid and inner.



CHAPTER 5

PHASE SHIFTER

In antenna theory, a **phased array** is an array of antennas in which the relative phases of the respective signals feeding the antennas are varied in such a way that the effective radiation pattern of the array is reinforced in a desired direction and suppressed in undesired directions.

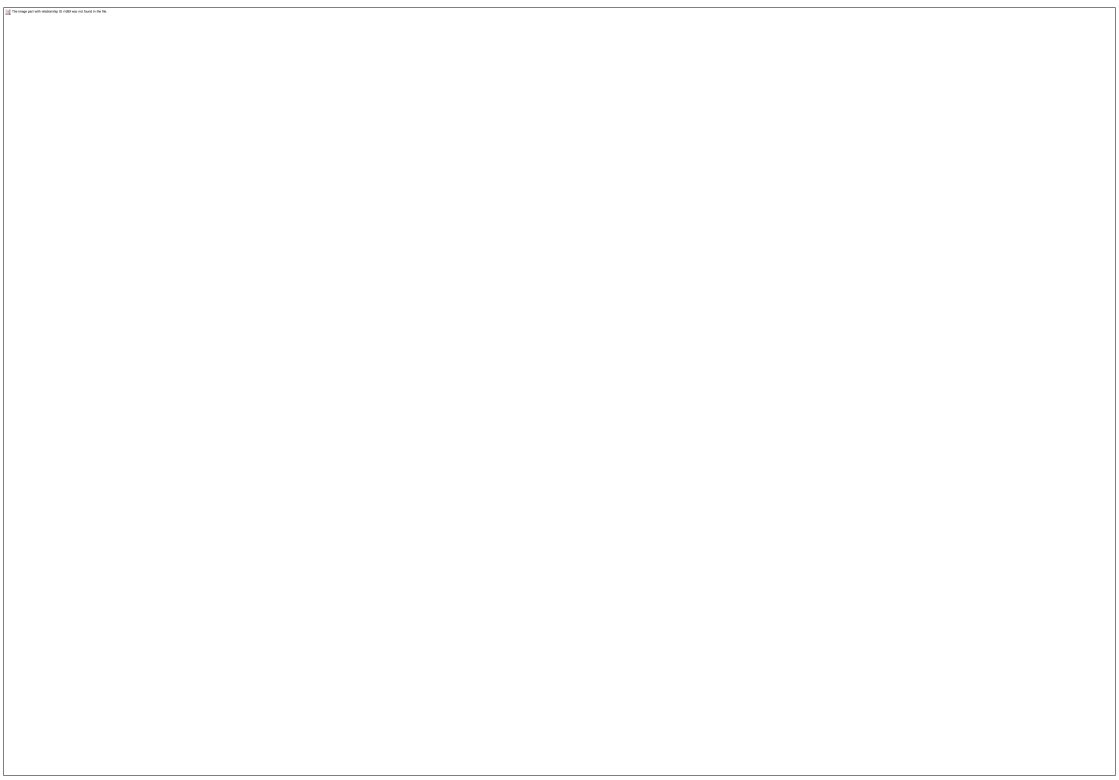


Fig. 5.1 Phase shifter overview

An antenna array is a group of multiple active antennas coupled to a common source or load to produce a directive radiation pattern. Usually, the spatial relationship of the individual antennas also contributes to the directivity of the antenna array. Use of the term "active antennas" is intended to describe elements whose energy output is modified due to the presence of a source of energy in the element (other than the mere signal energy which passes through the circuit) or an element in which the energy output from a source of energy is controlled by the signal input. One common application of this is with a standard multiband television antenna, which has multiple elements coupled together.

5.1 PRACTICAL DESIGN OF FIXED PHASE SHIFTER

A simple switched-line phase shifter is shown in below. The phase shift can easily be computed from the difference in the electrical lengths of the reference arm and the delay arm. The phase of any transmission line is equal to its length times its propagation constant; typically we use electrical degrees for this, not radians.

SPDT switches can be realized in a wide variety of ways, using FET, diode, or MEMS (micro-electro-mechanical systems) switches. The combined isolation of the two switches must exceed 20 dB in the design frequency band, or there will be ripple in the amplitude and phase response due to leakage of the "off" arm, sensitivities to FET parameters, etc.

Fig. 5.2 Switched line phase shifter topology

It is important to choose a switch technology appropriately for the frequency band of interest. PIN diode switches are often used through 18 GHz for "chip-and wire" construction (this practice is known as MIC, or microwave integrated circuit). In MMIC design (monolithic microwave integrated circuit), the switches are often realized with FETs, up into millimeterwaves. The weird thing here is that a diode is usually a better switch element than a FET, but when employed on a monolithic circuit, FETs can overcome their off-state capacitance by using a shunt inductor trick at very high frequencies (we will cover that topic at a future time in a section about microwave switches… UE). Diodes are almost never employed monolithically (exceptions are offered by TriQuint and M/A-COM), so they have to suffer the variations in wirebond inductance associated with MIC construction, and hence the frequency limitation.

An example of a millimeter-wave MMIC switched-line phase shifter is shown in below. The insertion loss of a switched-line phase shifter is dominated by the switch losses. Typical values are one dB loss per bit through X-band, 2 dB per bit at Ka band and 3 dB or more per bit at W-band. Two complimentary control signals are always required for switched line phase shifters.

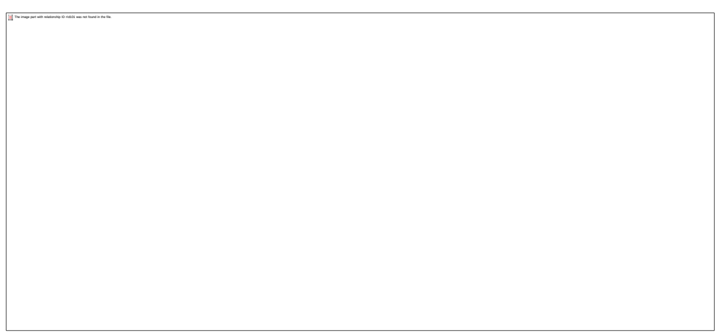


Fig 5.3 Example of 6-bit MMIC switched-line phase shifter

The figure shows the response of an ideal switched-line phase shifter. The difference in length between the reference arm and the delay arm is one-quarter wavelength at 10 GHz. Such a design would be used to provide a 90-degree phase shift at 10 GHz as shown (see the green trace on the plot). Switched-line phase shifters are often used for the two largest phase bits of a multi-bit phase shifter (180 and 90 degrees). Less complex circuits such as loaded-line elements can be used for 45 degree and lesser bits (see the loaded-line phase shifter discussion below).

Fig 5.4 Ideal switched-line phase shifter response, 10 GHz 90 degree bit

The down side of a switched line phase shifter is that it's RMS phase error degrades quickly over frequency. This is truly the poor man's phase shifter. If you want better performance, consider the high-pass/low-pass phase shifter as an upgrade. But with any filter topology, you'll need to consider the variations in performance with component tolerance.

5.2 WORKING OF PHASE SHIFTER

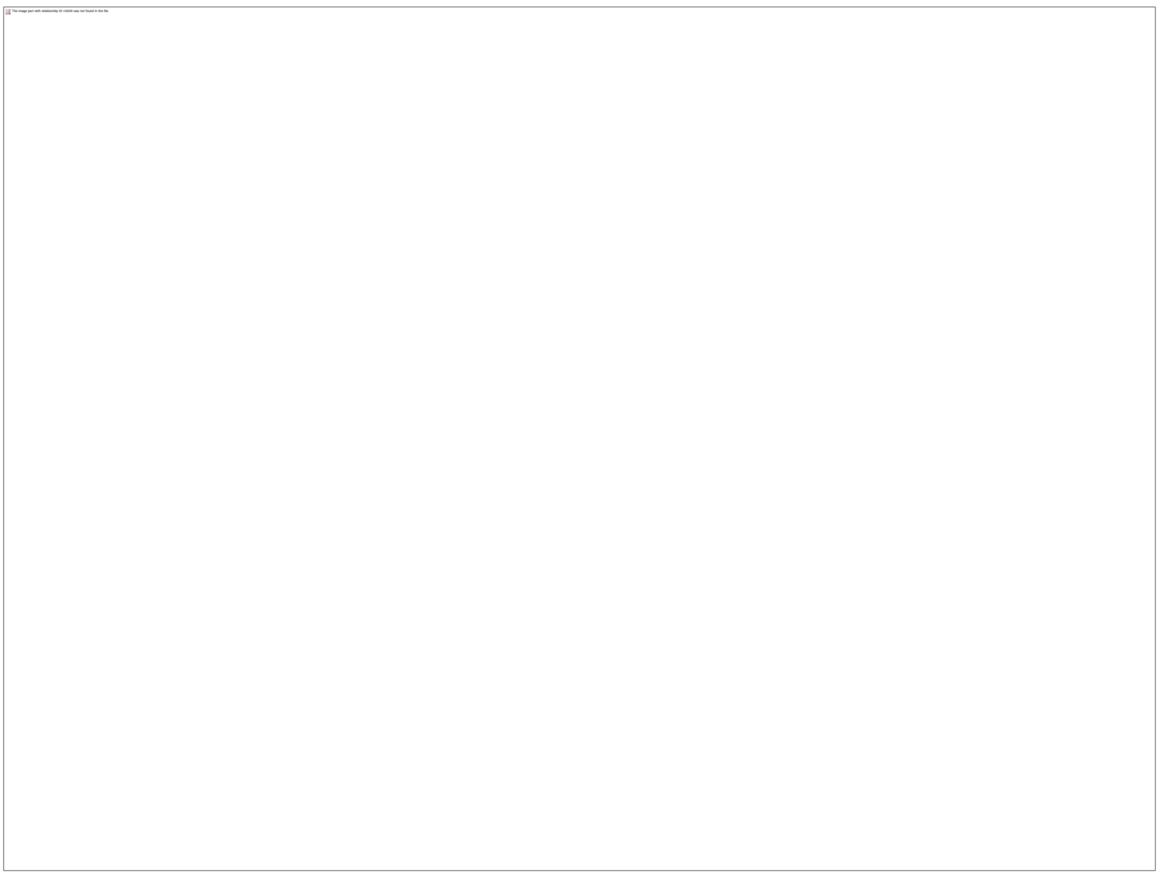
Figure 5.5 Fabricated Phase Shifter

This phase shifter consists of 8 micro strip lines with multiple of $\lambda/8$.we can change the complete main lobe of our antenna manually by connecting our 8 dipole array in different arrangements with this Phase shifter. So this phase shifter is basically acting as fixed phase shifter and providing us a phase shift 0 of 45 degree in complete circle.

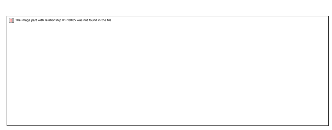
CHAPTER 6

WILKINSON POWER DIVIDER & ARRAY

The Wilkinson power divider is such a network in which the output ports are isolated while all the ports are matchedThe Wilkinson network can also be used as a power combiner because it is made up of passive components and hence reciprocal.



The scattering parameters for the common case of a 2-way equal-split Wilkinson power divider at the design frequency is given by

 5.1

Inspection of the S matrix reveals that the network is reciprocal ($S_{ij} = S_{ji}$), that the terminals are matched ($S_{11}, S_{22}, S_{33} = 0$), that the output terminals are isolated ($S_{23}, S_{32} = 0$), and that equal power division is achieved ($S_{21} = S_{31}$). A two port Wilkinson power divider is shown in following figure 6.1.

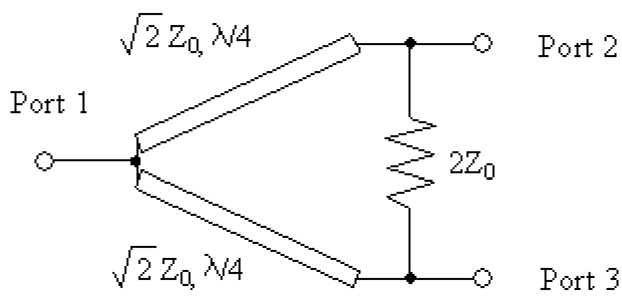


Figure 6.1 An Equal Divide Two port Wilkinson Power Divider

The arms are quarter-wave transformers of impedance $1.414Z_0$.When a signal enters port 1, it splits into equal-amplitude, equal-phase output signals at ports 2 and 3. Since each end of the isolation resistor between ports 2 and 3 is at the same potential, no current flows through it and therefore the resistor is decoupled from the input. The two output port terminations will add in parallel at the input, so they must be transformed to $2Z_0$ each at the input port to combine to Z_0. The quarter-wave transformers in each leg accomplish this; without the quarter-wave transformers, the combined impedance of the two outputs at port 1 would be $Z_o/2$. The characteristic impedance of the quarter-wave lines must be equal to $1.414Z_o$ so that the input is matched when ports 2 and 3 are terminated in Z_o.

6.1 WILKINSON POWER DIVIDER DESIGN IN ADS:

The Wilkinson power divider was designed in ADS momentum by using microstrip lines. When required $Z_o = 50\ \Omega$ then the impedance of the two arms is $1.414Zo = 70.7\Omega$ and the value of the resistor is $2Z_o = 100\ \Omega$. The design of Wilkinson power divider in ADS is shown in following Figure 6.2.

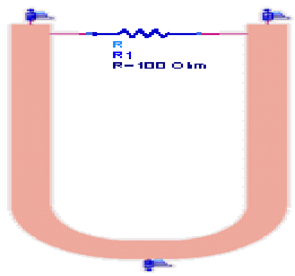


Figure 6.2 Two Port Wilkinson Power Divider in ADS

The results of the designed Wilkinson Power Divider are shown in Figure 6.3. It can be seen that a return loss of less than -35 dB has been achieved and almost equal power division of -3 dB has been achieved at the output ports.

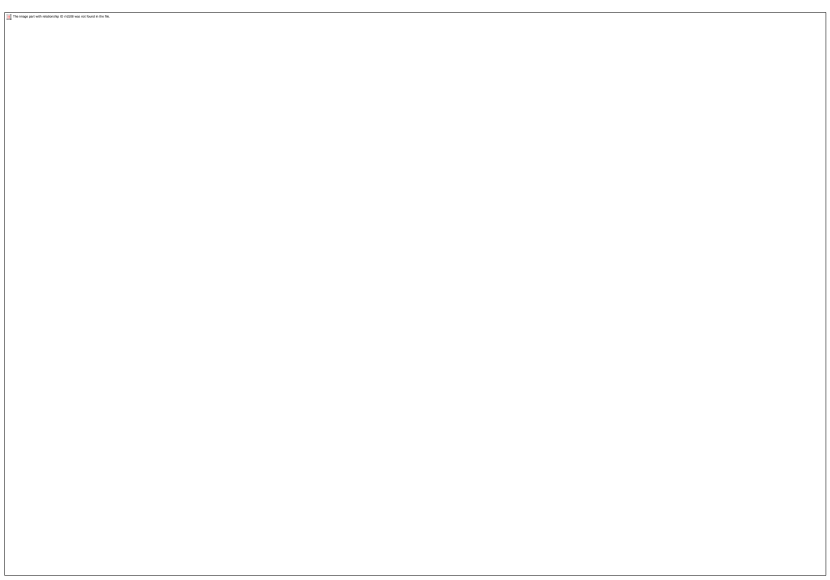


Figure 6.3 Simulation Results of Wilkinson Power Divider in ADS

6.2 POWER DIVIDER NETWORK:

As there are four patch antennas to be connected, it is required that three Wilkinson power dividers be used. These are interconnected by transmission lines of impedance Zo=50Ω. The length of the lines connecting the Wilkinson power dividers were optimized for maximum return loss at the input and equal power division at the four output ports. The design in ADS is shown in the Figure 6.4.

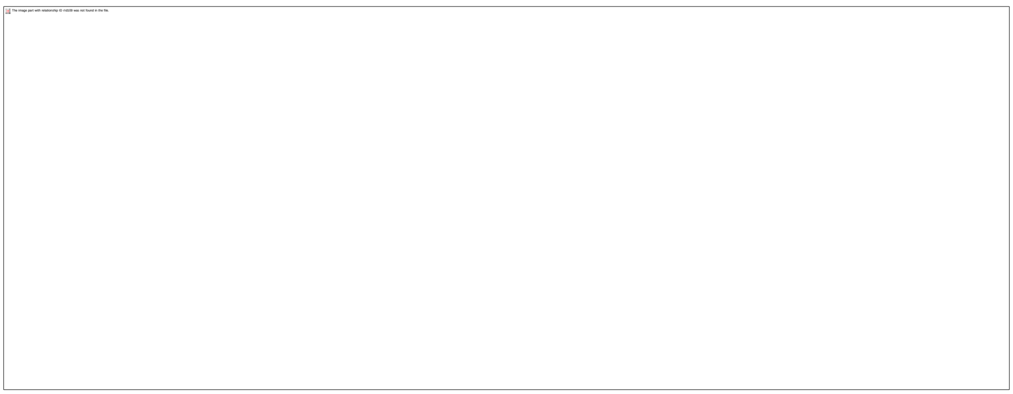


Figure 6.4 Complete Feed Network Design in ADS

The results of the feed network are shown in the Figure 6.4. It can be seen that the return loss at input port is less than **-24 dB** at the resonant frequency and the input power is divided equally among the four output ports and approximately -6 dB.

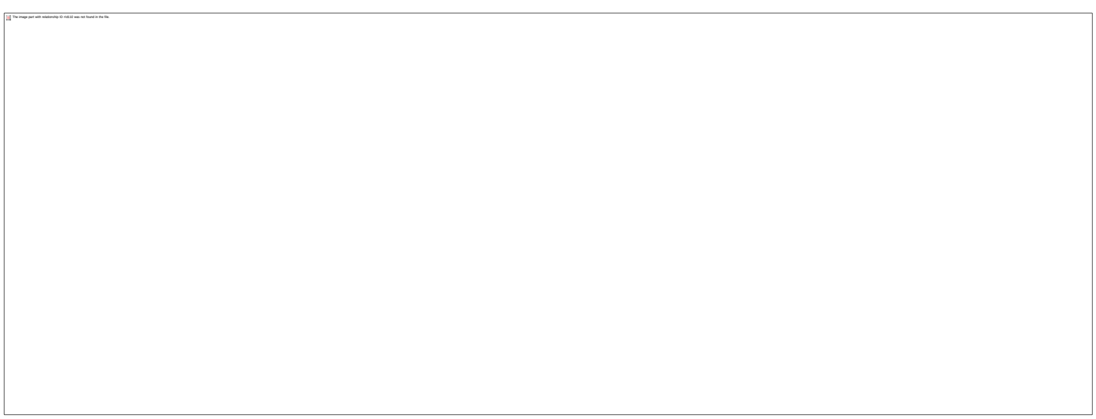


Figure 6.5 Complete Feed Network Simulation Results in ADS

6.3 COREL DRAWINGS OF POWER DIVIDERS

Fig 6.6 one to two power divider

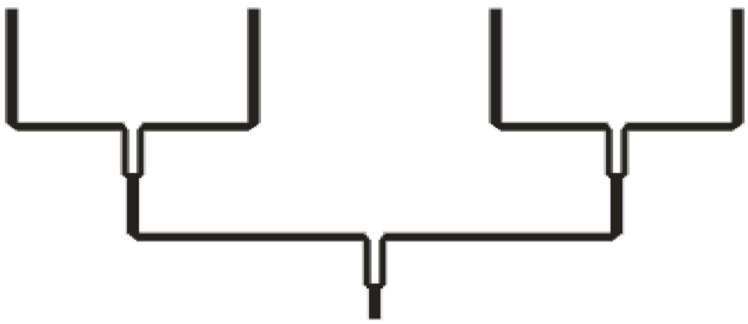


Fig 6.7 One to four power divider

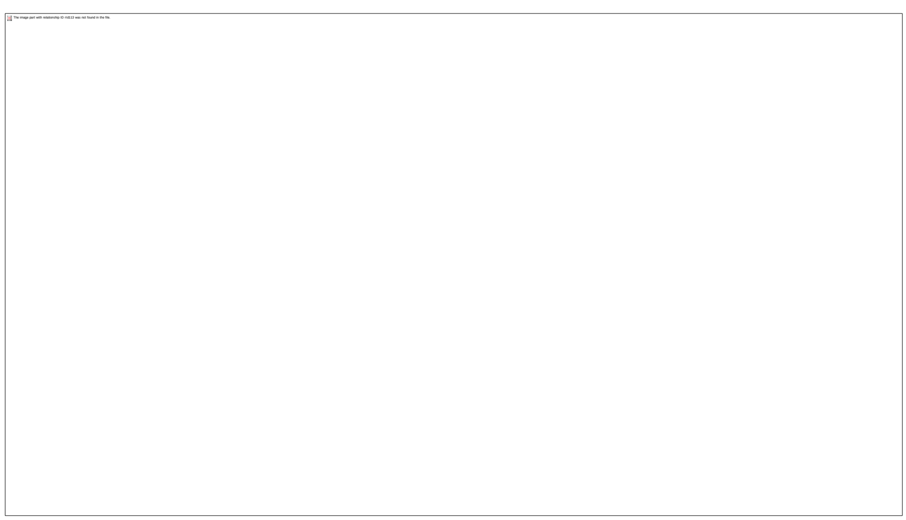


Fig 6.8 One to eight power divider

6.4 MANUFACTURE POWER DIVIDERS

Fig 6.9 One to two power divider

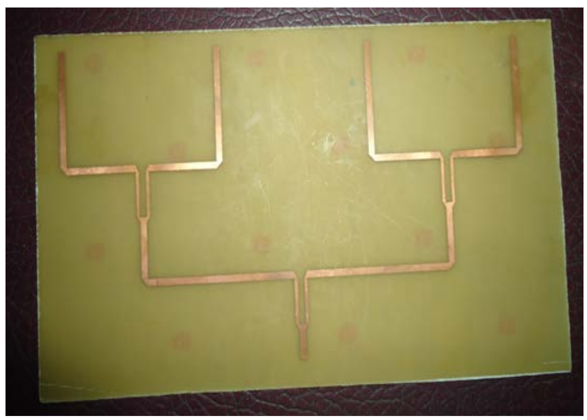


Fig 6.10 One to four power divider

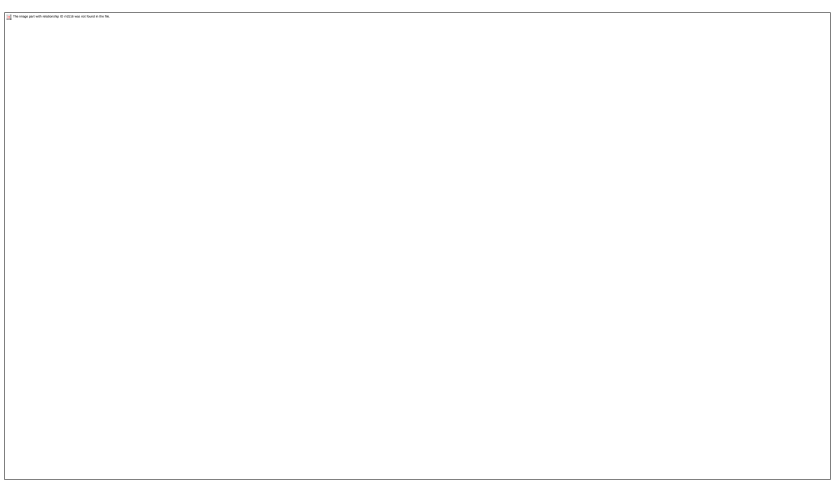


Fig 6.11 One to eight power divider

CHAPTER 7

COMPLETE RF FRONT END

The complete RF part was designed by connecting each patch antenna with a phase shifter and then connecting them through the feed network. The design is shown in Figure 7.1.

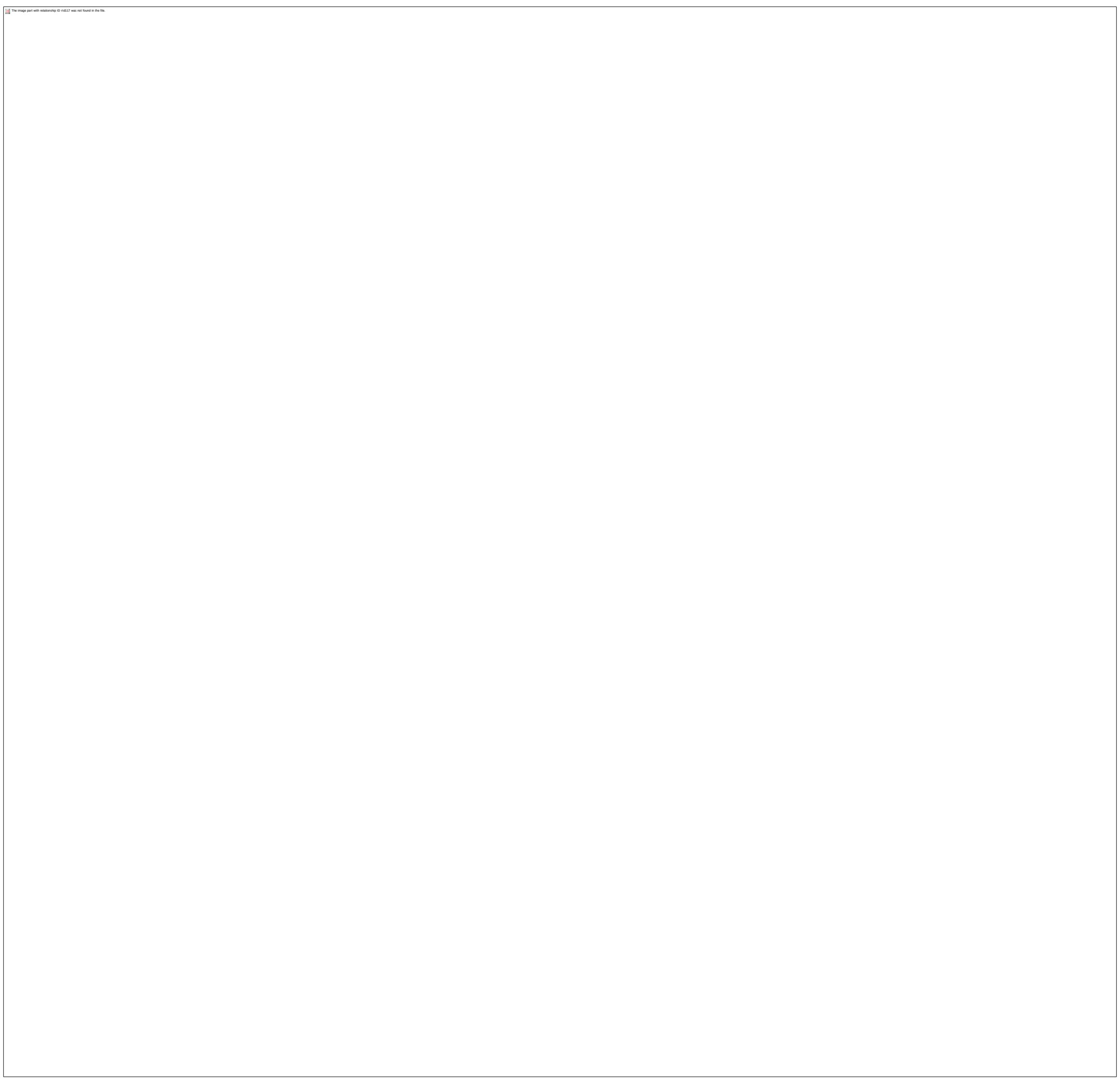
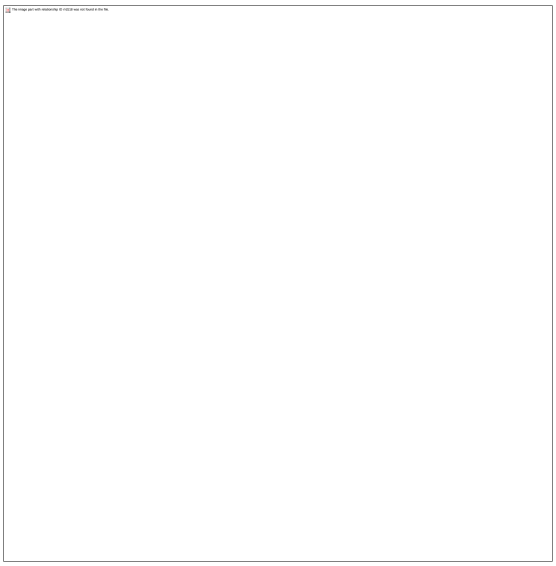


Fig. 7.1 Complete RF Part Design in ADS

7.1 BEAMFORMING SIMULATIONS USING DELAY LINE PHASE SHIFTING

Array with Transmission Line Phase Shifter at Angle 45degree is shown in Figure 7.2.



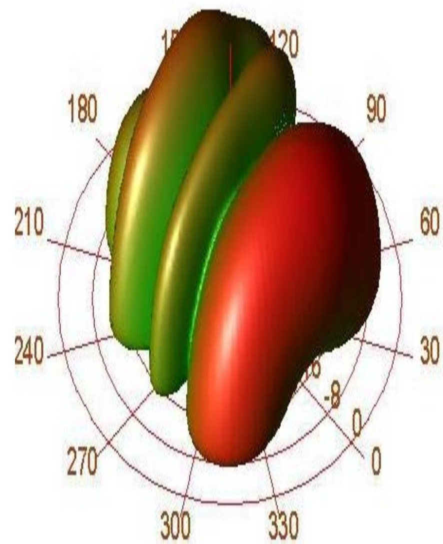


Fig 7.2 Design & Simulation Resultsof Array with Transmission Line Phase Shifter At45^0

7.2 MANUFACTURED BEAMFORMER'S PRACTICAL RESULT

The manufactured beamformer is shown in Figure 7.3.The total size of the structure 13cm ×10cm.

Fig 7.3 Manufactured Beam former

The structure was tested on Vector Network Analyzer and its return loss is shown in Figure 7.4.

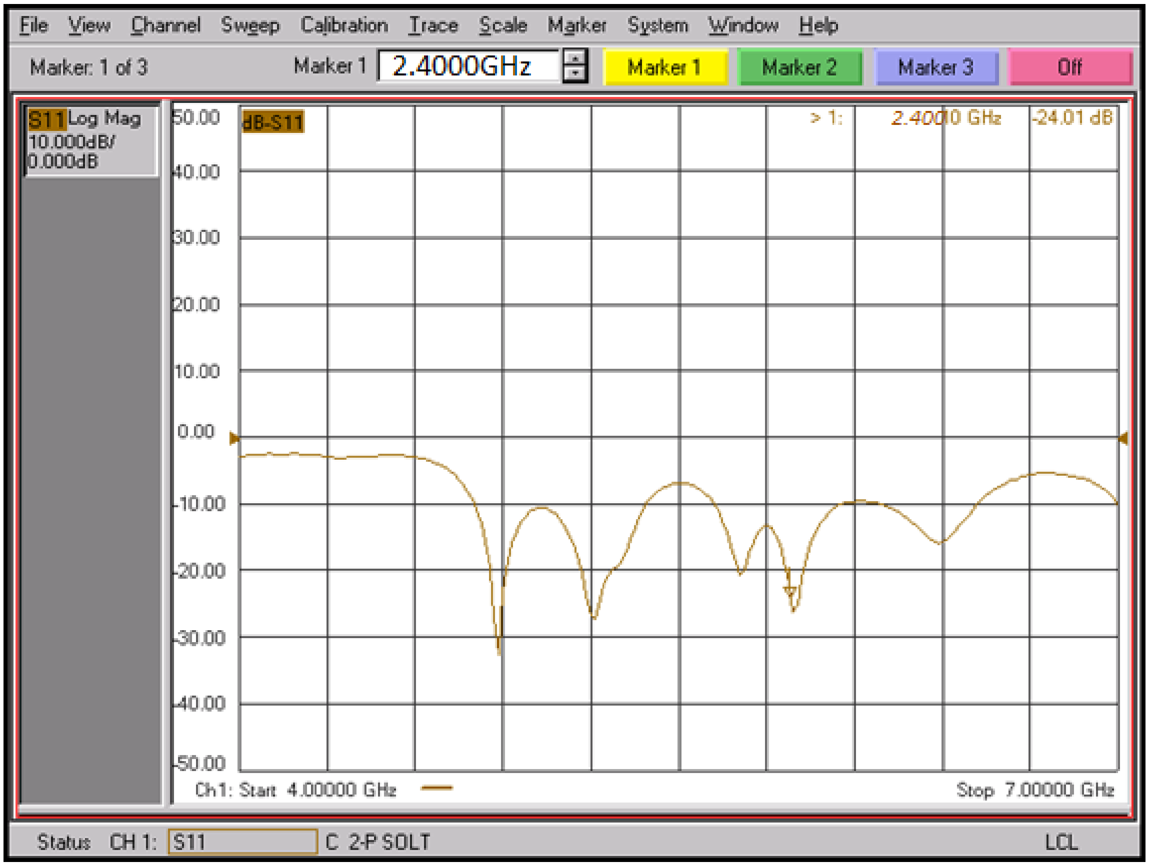
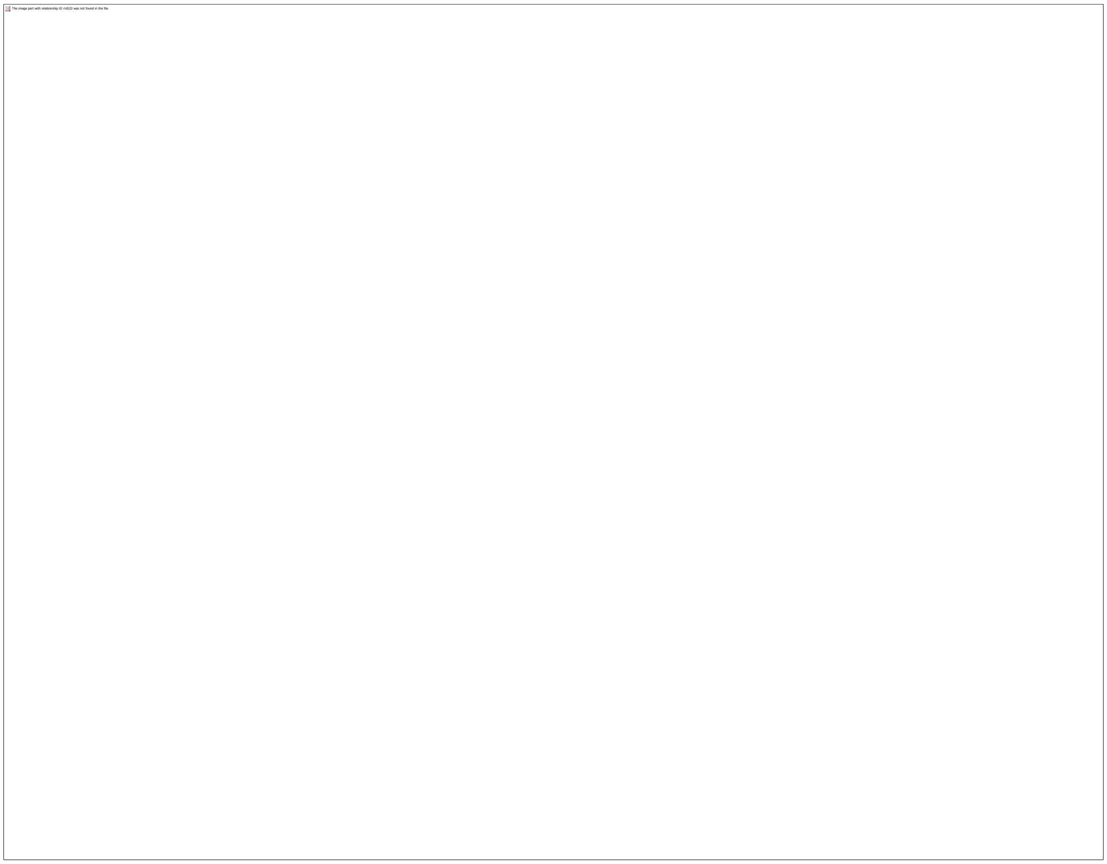


Fig. 7.4 Return Loss of Beam former

The Antenna was then place in Anechoic chamber and the radiation pattern was measured. The phase shifts were given accordingly to steer the maxima of the beam towards 12 degrees and the 3D and 2D results are shown in Figure 7.5.



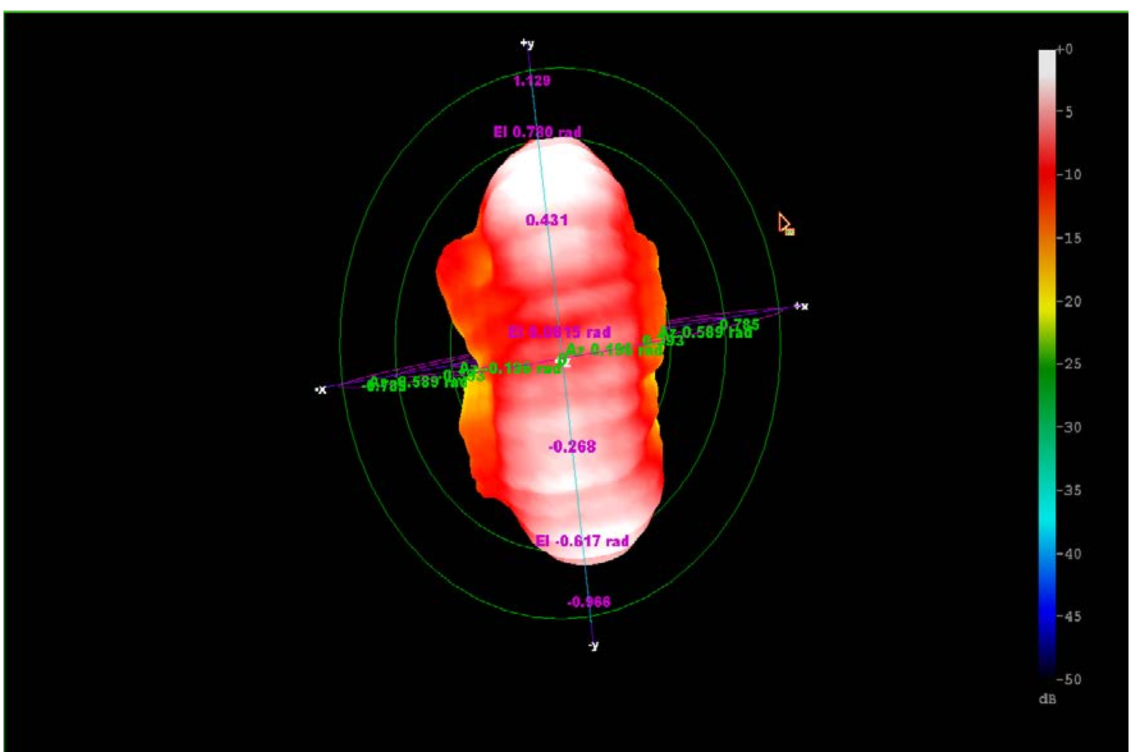
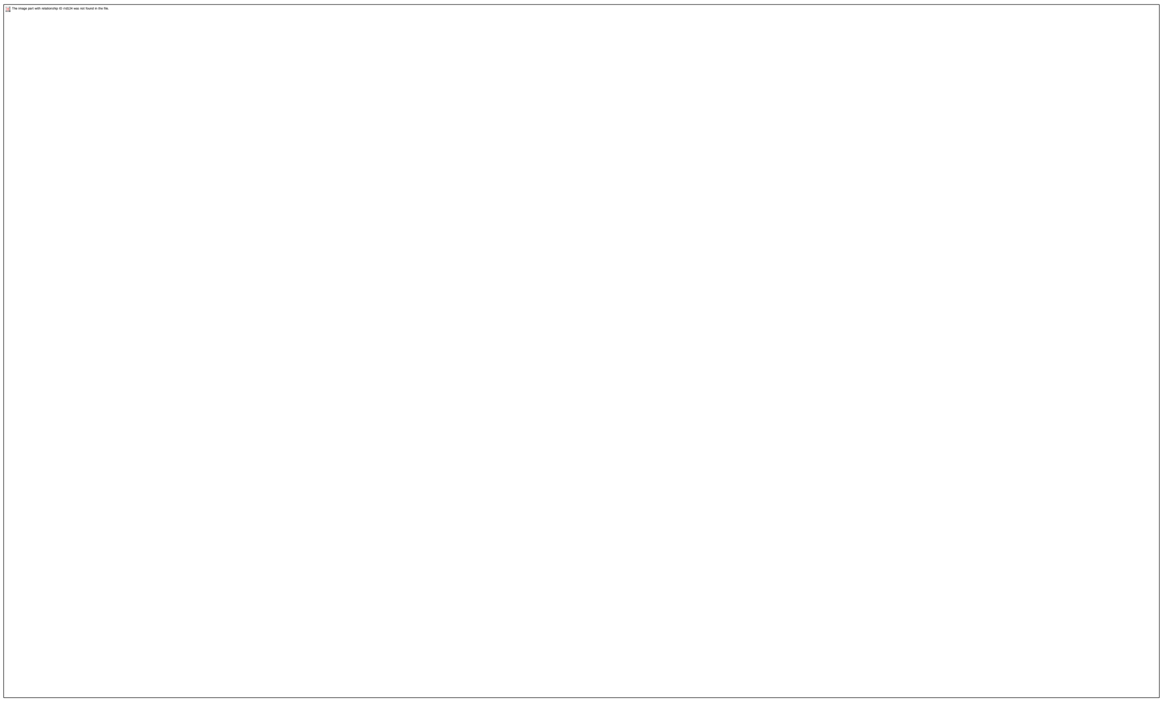


Fig 7.5 2D & 3D pattern of Beam Steered at 12^0

The phase shifts was then changed to steer the beam in the opposite direction i.e. -12 degrees and the patterns are shown in Figure 7.6.



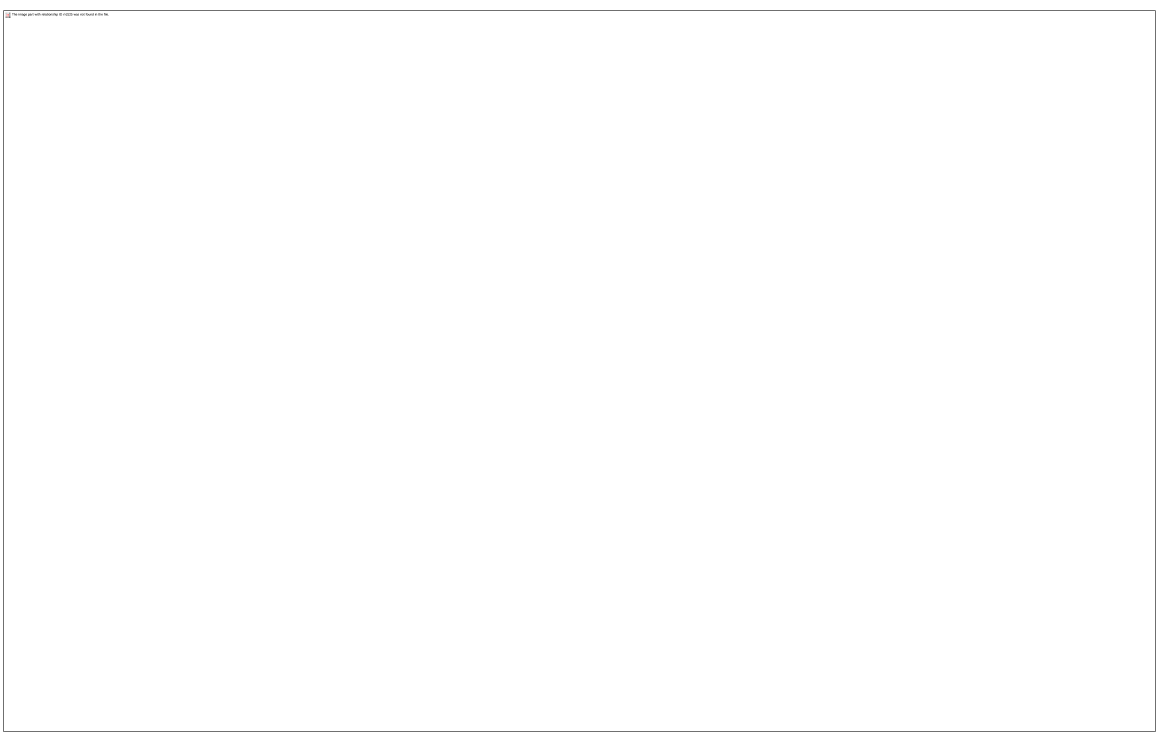


Fig 7.6 2D & 3D pattern of Beam Steered at -12^0

The phase shifts and voltages were then changed to steer the beam in the opposite direction i.e. 15 degrees and the patterns are shown in Figure 7.7.

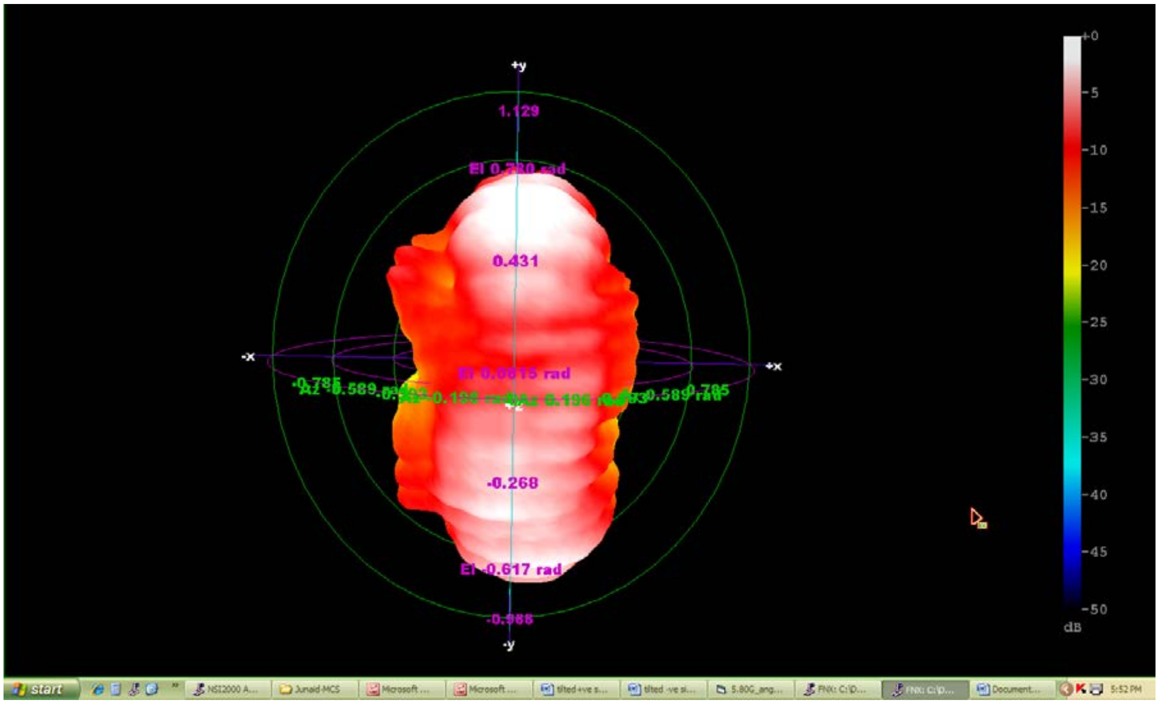


Fig 7.7 2D & 3D pattern of Beam Steered at 15^0

CHAPTER 8

APPLICATIONS

The relative amplitudes of constructive and destructive interference affects among the signals radiated by the individual antennas determine the effective radiation pattern of the array. A phased shifter may be used to point a fixed radiation pattern, orto scan rapidly in azimuth or elevation.

8.1 IEEE 802.11a WiFi

802.11 is a set of IEEE standards that govern wireless networking transmission methods. They are commonly used today in their 802.11a, 802.11b, 802.11g and 802.11n versions to provide wireless connectivity in the home, office and some commercial establishments. IEEE 802.11ais an amendment to the IEEE 802.11 specification that added a higher data rate of up to 54 Mbit/s using the 5 GHz band. It has seen widespread worldwide implementation, particularly within the corporate workspace. The amendment has been incorporated into the published IEEE 802.11-2007 standard.

This standard works at 5.8 GHz, which does not incorporate beamforming. We have designed simple, easy and low cost solution for introducing beamforming in IEEE 802.11a standard.

8.2 BROADCASTING

In broadcast engineering, beamformer are required to be used by many AM FM broadcast radio stations to enhance signal strength and therefore coverage in the city of license, while minimizing interference to other areas.

8.3 NAVAL USAGE

Smart Antenna radar systems are also used by warships of many navies. They allow a warship to use one radar system for surface detection and tracking (finding ships), air detection and tracking (finding aircraft and missiles) and missile uplink capabilities. Prior to using these systems, each surface-to-air missile in flight requiresdedicated fire-control radar, which meant that ships could only engage a small number of simultaneous targets.

8.4 OPTICS

Within the visible or infrared spectrum of electromagnetic waves it is also possible to construct optical phased arrays. They are used in wavelength multiplexers and filters for telecommunication purposes, laser beam steering, and holography. Synthetic array heterodyne detection is an efficient method for multiplexing an entire phased array onto a single element photo detector.

8.4 BEAM FORMING FOR LOW PROBABILITY OF INTERCEPT

In early standard wireless communications the transmission of the RF signal was dispersed evenly in all directions. This made interception of the RF signal easy for those eavesdroppers because all they had to know was the bandwidth and carrier frequency. They just needed an energy detector to determine if the received signal was just noise or if it was signal plus noise. Therefore, the probability of intercept was relatively high and had to rely on the upper layers security measures, such as data encryption for protection against intrusion. An area of research that has grown recently is providing security at the physical layer.

With the advent of smart antennas, wireless communications became more intelligent (or aware of its surroundings), and energy efficient. Smart antennas could use transmit beam forming to focus the RF signals in the direction of the user they wanted to communicate with. Also beam forming could be used on the receive side for rejecting any directional interferes. This situation made interception much more difficult for the eavesdropper since is he is no longer in direct line-of-sight of the communication. But a good eaves drop will still be able to intercept this signal with intelligent signal processing. This is because in traditional beam forming, the channel is slowly time varying, then beam forming vector is also slowly time varying, thus channel can be determined by the eavesdropper.

APPENDEX-A

USER MANUAL

INSTALLATION

Fix the Beam former firmly at the desired location. The placement should be such that the RF part as shown in Figure A.1 is perpendicular to the plane in which the beam is to be steered.

Figure A.1.RF Front End

This complete RF Front End will be connected to a transmitter or receiver through main port of Wilkinson power divider. Power of this RF Front End will depend upon the power of transmitter or receiver used. Wilkinson power divider will act as divider in transmitter mode and will act as combiner in receiver mode.

OPERATION

Figure A.2.phase shifter

The phase shift will be achieved while changing the connection of phase shifter in different arrangements with dipole array.

TROUBLE SHOOTING

If the beam has not shifted in the required direction then perform the following steps:

1. Check that the power of transmitter or receiver attached to the Beam former in turned ON and working correctly. Also check the current provided by the supply is 1A.

2. If the problem is not solved by step 1 then check that the supply voltages and ground terminals are properly attached to the labeled wires of the Beam former in the exact manner as labeled.

3. If the problem still persists then check the connections of phase shifter and Wilkinson power divider.

BIBLIOGRAPHY

1. Louay M.A. Jalloul and Sam. P. Alex, "Evaluation Methodology and Performance of an IEEE 802.16e System", Presented to the IEEE Communications and Signal Processing Society, Orange County Joint Chapter (ComSig), December 7, 2006. Available at: http://chapters.comsoc.org/comsig/meet.html
2. Microwave Sampling Beamformer—Prototype Verification and Switch Design by SadeghFarzaneh, Member, IEEE, and Abdel-RazikSebak, Senionr Member, IEEE
3. Antenna Theory - Analysis and Design by Constantine A. Balanis
4. Design and analysis of wideband planar monopole antennas using the multilevel fast multipole algorithm by Y. Chen, S. Yang, S. He, and Z. Nie
5. A Varactor Controlled Phase Shifter for PCS Base Station Applications- An application note
6. Microwave Engineering by David M. Pozar
7. A Smart Antenna Receiver Array Using a Single RF Channel and Digital Beamforming by Jonathan D. Fredrick, Student Member, IEEE, Yuanxun Wang, Member, IEEE, and Tatsuo Itoh, Fellow, IEEE
8. Ohira T, Suzuki Y, Ogawa H, Kamitsuna H. Megalithic Microwave signal processing for phased- array beam forming and steering. IEEE Trans Microwave Theory Tech 1997;45:2324-2332.
9. Design Formula for Inset Fed Microstrip Patch AntennaM. Ramesh and YIP KB Motorola, PINANG, MALAYSIA.
10. Mailloux RJ. Phased array antenna handbook. Artech House; 1994. p 480-490

11. Litva J. Digital beamforming in wireless communications. Artech House; 1996.

12. N. Novak, *Switched-Beam Adaptive Antenna System*, PhD thesis, TU Wien, Vienna, Austria, Nov.1999

13. EM Software & Systems (EMSS): *FEKO* Suite 4.1,Jul. 2003.

14. 3. M. Maier, *Definition Study of the T3D Antenna Array* ,EU Project EVK2-CT-2002-30004, IHF, TU Stuttgart

15. J.L. Butler, *Digital matrix and intermediate-frequency scanning* in R.C. Hansen, *Microwave scanning antennas, V*. 3, NY Academic press 1969, pp.241-268

A. Constantine Balanis, *Antenna Theory*, John Wiley & Sons, 1997
    a. Smith, D.J. (2005). *Air Band Radio Handbook (8th Edition)*. Sutton Publishing. pp. 104–105.

I. Keen R, Wireless Direction Finding(8th Edition), 1947, Iliffe, London

J. deRosa, L.A. (1979). "Direction Finding". In J.A. Biyd, D.B. Harris, D.D. King & H.W. Welch, Jr.. Electronic Countermeasures. Los Altos, CA: Peninsula Publishing.Hereford and B. Edgerly (2000). "457 kHz Electromagnetism and the Future of Avalanche Transceivers" (– Scholar search). International Snow Science Workshop (ISSW 2000). http://www.backcountryaccess.com/images/documents/457andFuture_000.pdf.

K. Titterington, B.; Williams, D. and Dean, D. (2007). Radio Orienteering - The ARDF Handbook. Radio Society of Great Britain. ISBN 9781-9050-8627-6

16. A. Derneryd, B. Johannison, *Adaptive base-station antenna arrays*, Ericsson Review No.3, 1999, pp.132ff

17. R.M.Buehrer et. al., *Intelligent antennas fo r wireless Communications – uplink*, Bell Labs Techn. Journal Vol. Jul.-Sept. 1999, pp. 73-103, 1999