CALIFORNIA STATE UNIVERSITY FRESNO

LYLES COLLEGE OF ENGINEERING

Department of Electrical and Computer Engineering

IMPLEMENTATION OF UNIFORM ANTENNA ARRAYS WITH BEAMSTEERING CAPABILITY AND PHASER CALIBRATION.

Under the guidance of Dr. Young W Kim

Submitted by

Madhushree Kadabur Sugunakar

ABSTRACT

IMPLEMENTATION OF UNIFORM ANTENNA ARRAYS WITH BEAMSTEERING CAPABILITY AND PHASER CALIBRATION.

Beamforming and Beam steering in Antenna are finding expanding use with frameworks like cellular telecommunications and specifically 5G just as numerous different wireless frameworks. This project mainly focuses on the utilization of the concepts of Phased Antenna Array to steer an antenna beam to the desired Direction Angle using Uniform Liner Antenna Array and Uniform Circular Antenna Array. The equations governing the technique of Beam steering are studied in detail and implemented using MATLAB. Beam steering is achieved for both Uniform Liner Antenna Array and Uniform Circular Antenna Array using MATLAB. This was further extended with the Hardware implementation of a uniform Linear antenna array to test for Beam steering capability using NI Universal Software Radio Peripheral (USRP) devices programmed using MATLAB.

The scope of the project was further extended by trying to calibrate the phase of the antenna arrays that are connected to the radios using the concepts of Mixers, which could be used as a phase detector.

Madhushree Kadabur Sugunakar

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Madhushree Kadabur Sugunakar

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Madhushree Kadabur Sugunakar

Thesis Author

Chairperson's name Prof. Reza Raeisi

Committee member's name Prof. Young W Kim

For the University Graduate Committee:

Dean, Division of Graduate Studies

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CHAPTER 1 INTRODUCTION

An Antenna is considered a transducer that can help in radiating electromagnetic energy in a required direction efficiently. Antennas can also act as a system for matching between the space and the source of the electromagnetic energy. These Antennas are available in different shapes and sizes based on the specific applications in which they are used. In order to enhance a few of the properties the antennas are being used individually or in the form of an array. This array has multiple sets of antennas or antenna elements that are operated together, this collection of antennae is together known as the Antenna array and this array together behaves as a single antenna. By changing the phase and magnitude of the signal that is fed to each of the antennae, the shape of the radiation pattern of the antenna can be controlled and this property also helps in electronically steering the beam of the antenna to desired directing [1]. This steering can be done just by making necessary changes to the phase of the signal fed to each of the antenna element in the antenna array without necessary changes to the structure of the antenna array.

As the radiated field from a single dipole is always uniform in a horizontal plane and it is not possible to direct them to the desired direction due to the bulky structure of the antennas. Thus, we require two or more antenna the lead to the concept of using a greater number of antennas in combination to form Antenna Array. The Antenna array also has an advantage that is so flexible that the antenna designer is able to obtain the greater directivity, lower side lobes, narrower beam, a beam that is steerable and can shape the radiation pattern easily [1]. In most of the cases, the antenna array has identical antenna elements unlike few which as differently dimensioned antenna elements. There are various configurations in which the antenna arrays could be arranged the most commonly used arrangement in a single dimension is linear arrangement and two-dimensional arrangement may contain planar grid or circular arrangement. Thus, this flexibility of the antenna arrays has led to numerous applications which include Electronic Beam Steering[1]. One of the best examples of Antenna array is Phased antenna array.

CHAPTER 2 PHASED ANTENNA ARRAY

In Antenna Theory, a phased array can be defined as an array of antennas in which the phases of each of the signal that is being fed to each antenna element are adjusted in a way to produce an effective Radiation Pattern of an entire antenna array can be set to the desired direction and the signal in the undesired direction can be suppressed.

The Phased array is also known as phased antenna Array [1]. A phased array antenna consists of multiple radiating elements, where each element has a phase shifter of its own. Thus, the signal that is formed with a phase shift is emitted from the radiating element. These signals undergo constructive interference in the desired direction and destructive interference in the undesired direction suppressing the unwanted signal. The increased phase shift is the direction in which the Main beam of the phased antenna array is pointed [4].

2.1 Uniform Linear antenna

A collection of sensor elements that are equally spaced along a straight line are collectively called a Uniform Linear Array (ULA). The sensor elements used can be of any type like a dipole antenna, a patch antenna, microstrip antenna, etc., but most common type of sensor element used in uniform antenna array is dipole antenna that is used for transmission and reception of electromagnetic waves over the air. Some time other sensors like acoustic sensors can also be used in air or under water[2]. Uniform linear antenna arrays can be used for different applications so that their requirement also vary with their applications, but they are most commonly used in the case when the improvement of Signal to Noise Ratio and the Improvement of Gain (Response) in a particular direction is required. The important property of this array is that it accepts the signal in one direction and is able to reject the signal that is coming from another direction[1].

Figure 1 shows the Uniform Linear antenna array with N Identical radiator or antenna elements that are arranged on the z-axis. These antenna elements are connected through a branched network are fed by a common oscillator. Here each of the branches consists of an attenuator (or amplifier) and a phase shifter that is connected in series to control the phase and amplitude of the signal that is fed to the elements in a given branch.

Now let's consider the far field region for any of the antenna radiating element called the Element electric-field intensity given by $\widetilde{E_e}(R,\theta,\phi)$ as shown in the equation 2.1 and can be expressed as the product of two functions which are the spherical propagation factor and given by $\frac{e^{-jkR}}{R}$ and $\widetilde{f_e}(\theta,\phi)$ which is the directional dependence of the electric field of the element[1] .

$$\widetilde{E_e}(R,\theta,\phi) = \frac{e^{-jkR}}{R}\ \widetilde{f_e}(\theta,\phi) \qquad 2.1$$

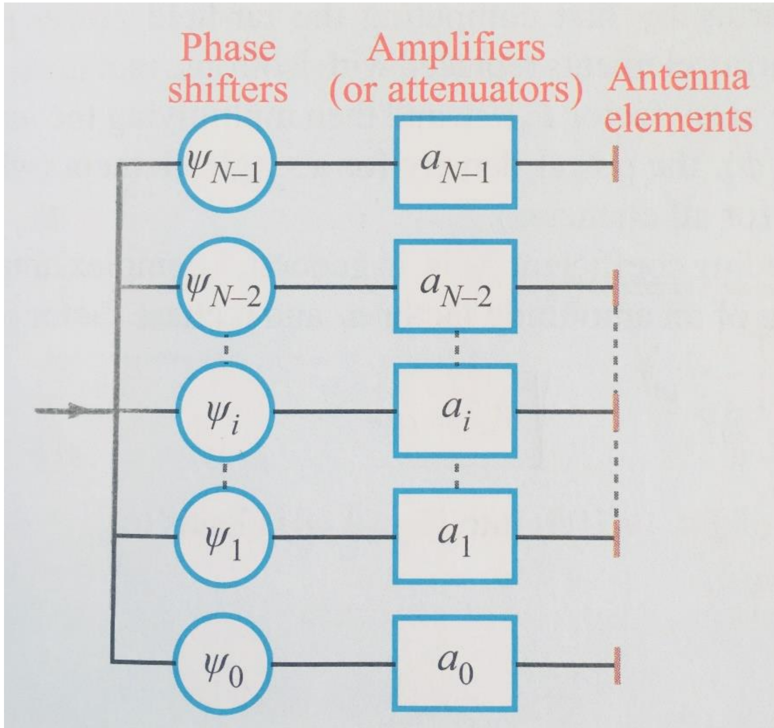


Figure 1 Branched network of Uniform Linear antenna array [1].

Considering the power density denoted by s_e is given by equation 2.2 below.

$$s_e(R,\theta,\phi) = \frac{1}{2\eta_0}\left|\tilde{E}_e(R\theta,\phi)\right|^2 = \frac{1}{2\eta_0 R^2}\left|\tilde{f}_\theta(\theta,\phi)\right|^2 \qquad 2.2$$

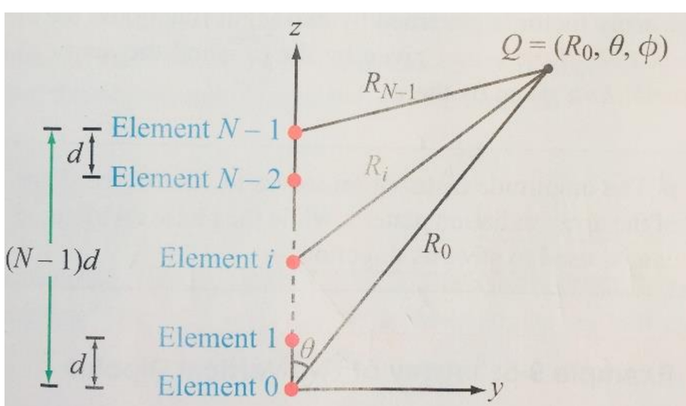


Figure 2 Uniform Linear antenna Array in the spherical coordinate system[1].

From figure 2 the far field due to element *i* at the range *Ri* observed from the point *Q* is given by the equation 2.3 below.

$$\tilde{E}_i(R,\theta,\phi) = A_i \frac{e^{-jkR_i}}{R_i} \quad \widetilde{f_e}(\theta,\phi) \qquad 2.3$$

Where,

$A_i = a_i \cdot e^{j\psi_i}$ - Complex feeding coefficient.

a_i, ψ_i – Amplitude and phase excitation respectively.

θ, ϕ – Angle of Azimuth and Angle of excitation respectively.

R_i – Range of the *ith* element.

k = 2.π / λ -Wave number.

λ = c / f -Wavelength.

f- Carrier frequency.

c- velocity of light in space.

Here in equation 2.3 A_i and R_i are different for each element but the factor $\widetilde{f_e}(\theta,\phi)$ remains the for all the elements are identical as they all exhibit the same directional pattern.

Now the total field at the observation point $Q(R_0,\theta,\phi)$ for due to N elements is the sum of all the individual electric field and can be expressed as the following equation 2.4.

$$\tilde{E}(R_0,\theta,\phi) = \sum_{i=0}^{N=1} \tilde{E}_i\,(R_i,\theta,\phi)$$

$$= \left[\sum_{i=0}^{N-1} A_i \frac{e^{(-jkR_i)}}{R_i}\right] \tilde{f}_e(\theta,\phi) \qquad 2.4$$

Where,

R_0- Range of the Zeroth element i.e. distance from the point of observation Q to the center of the coordinate system.

Let us now consider the concept of the far-field condition that states as the following equation 2.5 which states that the length of the array *l = (N-1) d* obey the equation 2.5. Where *d* is the spacing between the antenna element. Here the range R_0 should be larges so that,

$$R_0 \geq \frac{2l^2}{\lambda} = \frac{2(N-1)^2\, d^2}{\lambda} \qquad 2.5$$

The above equation 2.5 can be used to neglect the difference in the distances of the antenna elements from the observation point Q. Thus we can consider that $R_i = R_0$ in equation 2.4 for all i.According to the parallel-ray approximation the phase part of the propagation factor we consider the following equation 2.6. and this can be shown in figure 3.

$$R_i \approx R_0 - z_i \cos\theta = R_0 - i\, d \cos\theta \qquad 2.6$$

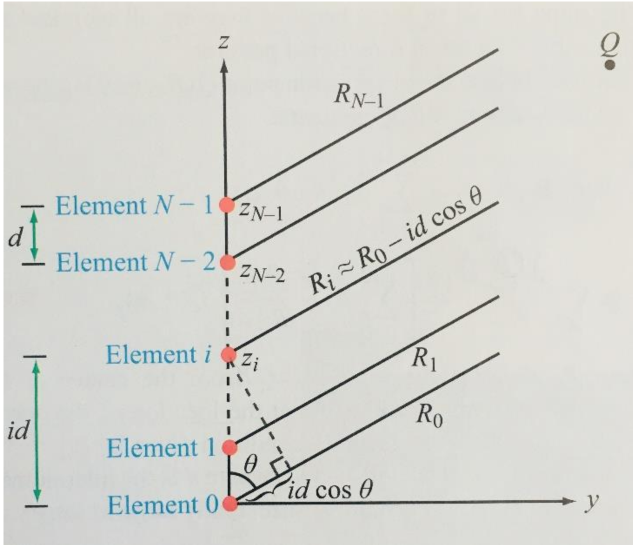


Figure 3 Uniform linear antenna array with far-field observation where rays between the antenna elements becoming parallel[1].

Where $z_i = id$ is the distance between the zeroth element and the ith element. Using equation 2.5 and 2.6, equation 2.4 becomes.

$$\tilde{E}(R_0, \theta, \phi) = \tilde{f}_e(\theta, \phi)\left(\frac{e^{-JkR_0}}{R_0}\right).\left[\sum_{i=0}^{N-1} A_i e^{(jk\, d\cos(\theta))}\right] \qquad 2.7$$

The power density of the antenna array is given by equation 2.8

$$S(R_0, \theta, \phi) = \frac{1}{2\eta_0}\left|\tilde{E}(R_0, \theta, \phi)\right|^2$$

$$= \frac{1}{2\eta_0 R_0^2} \left|\tilde{f}_e(\theta,\phi)\right|^2 \left|\sum_{i=0}^{N-1} A_i e^{(jk\,d\cos(\theta))}\right|^2$$

$$= S_e(R_0,\theta,\phi) \left|\sum_{i=0}^{N-1} A_i e^{(jk\,d\cos(\theta))}\right|^2 \qquad 2.8$$

The equation 2.8 can be expressed as the product of two factors, where the first term $S_e(R_0,\theta,\phi)$ is called as the power density of the radiated energy of an individual element and the second term the Array factor. The array factor is given equation 2.9 and the power density is given by the equation 2.10. The equation 2.10 is called the pattern multiplication principle.

$$F_a(\theta) = \left|\sum_{i=0}^{N-1} A_i e^{(jk\,d\cos(\theta))}\right|^2 \qquad 2.9$$

$$S(R_0,\theta,\phi) = S_e(R_0,\theta,\phi)\, F_a(\theta) \qquad 2.10$$

Where,

$A_i = a_i e^{j\psi_i}$ – Feeding coefficient(Amplitude and phase excitation).

a_i – Amplitude factor.

ψ_i – Phase factor.

Now by using the equation Feeding coefficient in equation 2.9 it becomes

$$F_a(\theta) = \left|\sum_{i=0}^{N-1} a_i e^{j\psi_i} . e^{(jk\,d\cos(\theta))}\right|^2 \qquad 2.11$$

From equation 2.11 it can be concluded that the Array factor depends on the two terms namely a_i as Array Amplitude distribution and ψ_i as Array Phase distribution. So, the shape of the Array Radiation pattern and the Beam can be steered to different direction using phase distribution[1].

2.2 Beam steering in Uniform linear Antenna Array

Consider a Uniform Linear Antenna array with N antenna elements and the considering that each antenna has different phases and has the feeding coefficient as ψ_0 to ψ_{N-1}. For the beam steering, we try to incorporate the phase delay between the element to electronically steer the antenna beam to the desired direction of the θ_0 (Angle of Azimuth). Let us consider the linear phase on the antenna array, where $\psi_i = -i\delta$ for all i= 0, 1,2…..*N-1*. and δ is the incremental Phase delay[1].

Now by replacing the value of where $\psi_i = -i\delta$ in the equation 2.11 we get equation 2.12 as shown below. This can also be seen in figure 4.

$$F_a(\theta) = \left|\sum_{i=0}^{N-1} a_i e^{-ji\delta} . e^{(jk\,d\cos(\theta))}\right|^2 \qquad 2.12$$

$$= \left|\sum_{i=0}^{N-1} a_i . e^{(j.i.(k\,d\cos(\theta)-\delta))}\right|^2$$

$$= \left|\sum\nolimits_{i=0}^{N-1} a_i . e^{(j.i.\gamma')}\right|^2 = F_a(\gamma') \qquad 2.13$$

Now we have

$$\gamma' = (k\,d\cos(\theta) - \delta) \qquad 2.14$$

Now replacing θ with θ_0 in equation 2.14 we can find the phase delay of the antenna elements as shown in equation 2.15.

$$\delta = k\,d\cos(\theta_0) \qquad 2.15$$

Where θ_0 -Steer angle.

Steer angle is the angle that defines the direction in which the antenna beam is to be steered.

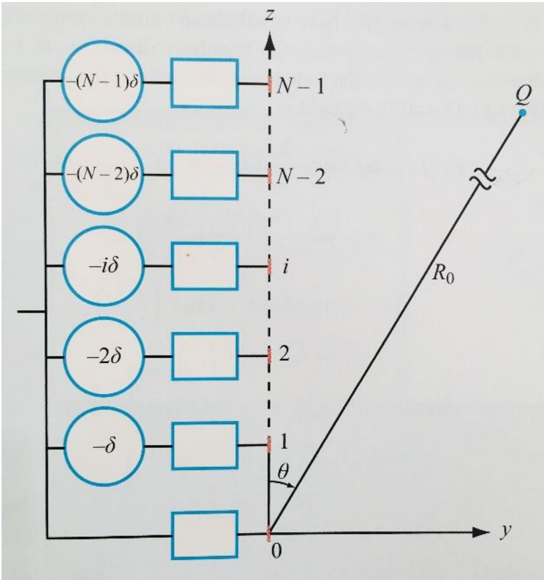


Figure 4 Uniform linear antenna array with a phase delay between the elements[1].

The Design of a Uniform Linear antenna is done using the MATLAB and is shown in the design section.

2.3 Uniform Circular Antenna

The Uniform Circular Antenna is an arrangement of antenna elements in a circular manner in the form of a ring with a Radius a and with a uniform separation between the antenna elements. The uniform circular antenna has been used as smart-antennas because of their ability to steer the beam to the desired direction[3]. Figure 5 shows the Uniform Antenna array which is arranged with its elements on the XY-plain in a spherical coordinate system. The Array factor of the uniform circular antenna is expressed as below.

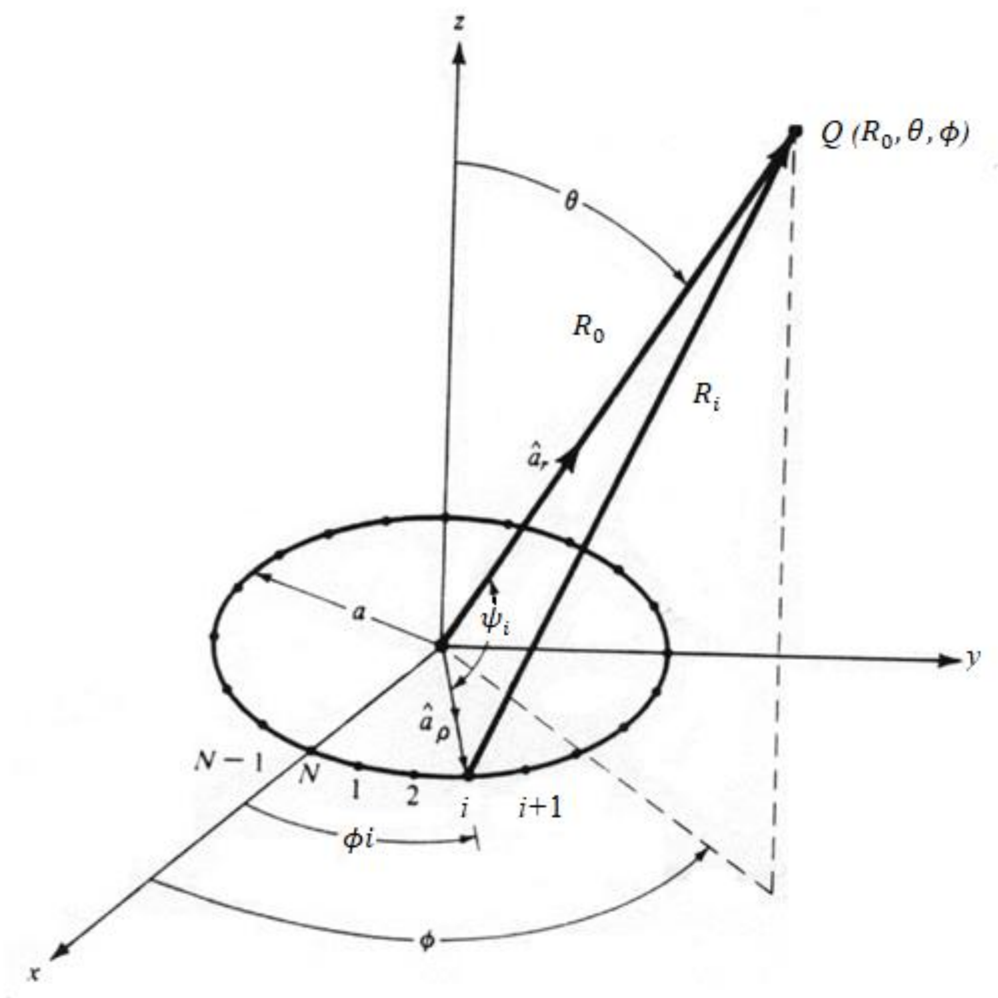


Figure 5 Uniform Antenna Array in a Spherical Coordinate system[3].

From the previous session it is clear that the total field at the observation point $Q(R_0, \theta, \phi)$ for due to N elements is the sum of all the individual electric field and can be expressed as the following equation 2.4.

$$\tilde{E}(R_0,\theta,\phi) = \sum_{i=0}^{N=1} \tilde{E}_i\,(R_i,\theta,\phi)$$

$$= \left[\sum_{i=0}^{N-1} A_i \frac{e^{(-jkR_i)}}{R_i}\right] \tilde{f}_e(\theta,\phi) \qquad 2.4$$

Where the R_i being the range of the *ith* element can be expressed as below shown in the equation as equation 2.16.

$$R_i = \sqrt{R_0^2 + a^2 - 2aR_0 \cos\psi_i} \qquad 2.16$$

If we consider far-field then the value of $R_0 >> a$ then the equation 2.16 becomes,

$$R_i \approx R_0 - a cos\,\psi_i \approx R_0 - a(\hat{a}_{\rho_i}\ .\hat{R}_0) \qquad 2.17$$

Considering the rectangular coordinate system we have,

$$\hat{a}_{\rho_i} \ = \hat{x}\, cos\,\phi_i + \hat{y}\, sin\,\phi_i$$

$$\hat{R}_0 = \hat{x}\, sin\,\theta\, cos\,\phi + \hat{y}\, sin\,\theta\, sin\,\phi + \hat{Z} \cos\theta$$

Substituting the values of $\hat{a}_{\rho_n}$ *and* $\hat{R}_0$ in equation 2.17 we have the equation 2.18 as shown below, here R_i for the phasor term is approximated as shown in equation 2.18 and for the amplitude, the term is approximated as shown in equation 2.19 for values of *i*.

$$R_i = R_0 - a\, sin\,\theta\, cos(\phi - \phi i) \qquad 2.18$$

$$\frac{1}{R_i} = \frac{1}{R_0} \qquad 2.19$$

So thereby using these approximations in equation 2.18 and 2.19, we re-express equation 2.4 as below equation 2.20.

$$\tilde{E}(R_0,\theta,\phi) = \left[\frac{e^{(-jkR_0)}}{R_0} \sum_{i=0}^{N-1} A_i e^{(jk\, a\, sin\,\theta\, cos(\phi-\phi i))}\right] \tilde{f}_e(\theta,\phi) \qquad 2.20$$

The power density of the antenna array is expressed as below and calculated using equation 2.21

$$S(R_0,\theta,\phi) = \frac{1}{2\eta_0}\left|\tilde{E}(R_0,\theta,\phi)\right|^2$$

$$= \frac{1}{2\eta_0 R_0^2}\left|\tilde{f}_e(\theta,\phi)\right|^2 \left|\sum_{i=0}^{N-1} A_i e^{(jk\, a\, sin\,\theta\, cos(\phi-\phi i))}\right|^2$$

$$= S_e(R_0,\theta,\phi)\left|\sum_{i=0}^{N-1} A_i e^{(jk\, a\, sin\,\theta\, cos(\phi-\phi i))}\right|^2$$

2.21

The equation 2.21 can be expressed as the product of two factors, where the first term $S_e(R_0, \theta, \phi)$ is called as the power density of the radiated energy of an individual element and the second term the Array factor. The array factor is given equation 2.22 and the power density is given by the equation 2.23. The equation 2.10 is called the pattern multiplication principle.

$$F_a(\theta, \phi) = \left| \sum_{i=0}^{N-1} A_i e^{(jk\, a \sin\theta \cos(\phi - \phi i))} \right|^2 \qquad 2.22$$

$$S(R_0, \theta, \phi) = S_e(R_0, \theta, \phi)\, F_a(\theta, \phi) \qquad 2.23$$

Where,

$A_i = a_i e^{j\psi_i}$ – Feeding coefficient (Amplitude and phase excitation).

a_i – Amplitude factor.

ψ_i – Phase factor.

θ, ϕ – Angle of Azimuth and Angle of excitation respectively.

R_0- Range or the Distance from the point of observation Q to the center of the Uniform Circular Antenna Array.

R_i – Range of the *ith* element.

ϕi =(*2 π i / N*) – Angular position of the *i*th antenna element.

k = 2.π / λ -Wave number.

λ = c / f -Wavelength.

f- Carrier frequency.

c- velocity of light in space.

Now by using the equation Feeding coefficient in equation 2.22 it becomes

$$F_a(\theta, \phi) = \left| \sum_{i=0}^{N-1} a_i e^{j\psi_i} e^{(jk\, a \sin\theta \cos(\phi - \phi i))} \right|^2 \qquad 2.24$$

From equation 2.24 it can be concluded that the Array factor depends on the two terms namely a_i as Array Amplitude distribution and ψ_i as Array Phase distribution. So, the shape of the Array Radiation pattern and the Beam can be steered to different direction using phase distribution.

2.4 Beam steering in Uniform Circular Antenna Array.

Consider a Uniform circular Antenna array with N antenna elements that are arranged in the form of a Ring on the XY-plane and let $Q\ (R_0, \theta, \phi)$ be the point of observation which is the function of Range, Angle of Azimuth and Angle of Excitation. Then we consider that each antenna has different phases and has its feeding coefficient as ψ_0 to ψ_{N-1}. For the Beam steering, we try to incorporate the phase delay between the element to electronically steer the antenna beam to the desired direction of the $(\theta_{0,}\phi_0)$, (Angle of Azimuth and Angle of elevation of the desired direction). Let us consider the linear phase on the antenna array, where $\psi_i = \delta_i$ for all *i*= 0, 1,2…..*N-1.* and δ is the incremental Phase delay.

Now by replacing the value of where $\psi_i = \delta_i$ in the equation 2.24 we get equation 2.25 as shown below.

$$F_a(\theta,\phi) = \left|\sum_{i=0}^{N-1} a_i e^{j\delta_i} e^{(jk\,a\,sin\,\theta\,cos(\phi-\phi i))}\right|^2 \qquad 2.25$$

$$= \left|\sum_{i=0}^{N-1} a_i . e^{(j(k\,a\,sin\,\theta\,cos(\phi-\phi i)+\delta_i))}\right|^2$$

$$= \left|\sum_{i=0}^{N-1} a_i . e^{(j\gamma')}\right|^2 = F_a(\gamma') \qquad 2.26$$

Now we have

$$\gamma' = k\,a\,sin\,\theta\,cos(\phi - \phi i) + \delta_i \qquad 2.27$$

The maximum value of Array factor is obtained when all the term of phase in 2.26 are equal to unity or can also be represented as below in equation 2.26

$$k\,a\,sin\,\theta\,cos(\phi - \phi i) + \delta_i = 2m\pi \qquad \text{where } m=0,\pm 1,\pm 2, \text{ all } i \qquad 2.26$$

The Maximum (m=0) can be defined by direction $(\theta_{0,}\phi_0)$ where,

$$\delta_i = -k\,a\,sin\,\theta_0 \cos(\phi_0 - \phi_i) \qquad \text{for all } i=0,1,2\ldots.N\text{-}1. \qquad 2.28$$

Here equation 2.28 can be used to determine the phase of each antenna element to steer the beam in the direction of $(\theta_{0,}\phi_0)$.

All the implementations are done using MATLAB.

CHAPTER 3: ADAPTIVE BEAMFORMING

Adaptive beamforming can be defined as a technique of receiving the signal of Interest (SOI) from a particular direction whereas adaptively suppressing the interfering signals from the undesired direction by using the Antenna Array. This technique enables the automatic optimization of the antenna array pattern by adjustment to the elemental control weight until a particular objective function is being satisfied. Adaptive Beamforming is considered to be an effective method to separate the desired signals from the Interference signal[5].

Beamforming has a wide range of application in sonar, radar, microphone array, speech processing, and wireless communication, which has recently added on to its applications. Here the use of antenna array together with some signal processing Algorithms near the base stations have offered the possibility to explore the spatial dimension for separating the multiple cochannel users. This has the advantage of wide area coverage and increased channel capacity. In such systems, the array beamformers use these spatial dimensions to reduce the noise, interference, and fading of the desired signal. In the beamformer, the output of each antenna element is combined linearly after they were scaled by the corresponding weights. This technique helps in the optimization of the antenna array to obtain a maximum gain in a desired particular direction and try to null the interference in another direction [6].

Considering a Beamformer with an output *y(n)* at a time *n* is given by the linear combination of data from N antenna elements which has the input vector as *x(n)* and *w(n)* being the weight vector as shown in the equation 3.1.

$$y(n) = w^{H}(n) * (n) \qquad 3.1$$

Where the weight vector can be given as shown below

$$w(n) = \sum_{i=0}^{N-1} w_i \qquad 3.2$$

$$x(n) = \sum_{i=0}^{N-1} x_i \qquad 3.3$$

In this algorithm, we also consider the matrix inverse operation and use the immediate gradient vector $\nabla J(n)$ for upgrading weight vector so the weight vector at time n+1 can be given as shown in the equation 3.4.

$$W(n+1) = W(n) + 0.5.\,\mu[\nabla J(n)] \qquad 3.4$$

Where,

μ- step size parameter

This step size parameter controls the convergence speed and its value lies between 0 and 1. The Minimum value of μ may lead to the slow convergence and high-quality estimation of the cost function and vice-versa, so an optimum value of μ is selected which leads to consistency over least value can disappear at equation 3.5

$$0 < \mu < (1/\lambda) \qquad 3.5$$

The Instantaneous Gradient vector $\nabla J(n)$ is given by equation 3.6, an exact value of $\nabla J(n)$ cannot be found because the covariance matrix R and cross-correlation vector p is required [7].

$$\nabla J(n) = -2p(n) + 2R(n).W(n) \qquad 3.6$$

$$R(n) = X(n)\,X^H(n) \qquad 3.7$$

$$p(n) = d(n) * X(n) \qquad 3.8$$

By substituting 3.6, 3.7 and 3.8 in 3.4 we obtain the equation

$$W(n+1) = W(n) + 0.5.\,\mu[-2p(n) + 2R(n).W(n)]$$

$$W(n+1) = W(n) + \mu\,X(n)\,[d^*(n) - X(n).W(n)]$$

$$W(n+1) = W(n) + \mu\,X(n)\,[e^*(n)] \qquad 3.9$$

Now the desired Signal can be found using the following Equations below

$$y(n) = w^H(n)x(n)$$

$$e(n) = \;[d(n).y(n).W(n+1)]$$

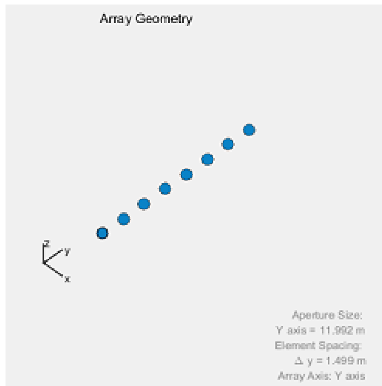
$$e(n) = \;W(n) + \;\mu\,X(n)\,[e^*(n)] \qquad 3.10$$

CHAPTER 4 DESIGN AND SIMULATION

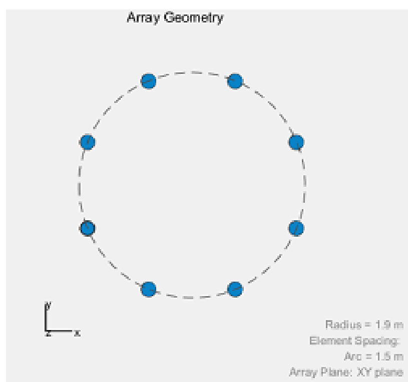
4.1 Design of Antenna Array.

4.1.1 Design of a Uniform Linear antenna array.

Figure 5 show the design of a Uniform linear antenna which is made up of N=8 antenna elements and is separated by a separation which is equal to half of the wavelength ($\lambda/2$). The elements used in the antenna array are simple dipole antennas. The antenna elements are placed on the y-axis which is called as the array axis. The total length of the uniform linear antenna array is 11.992m where the antenna separation is around 1.5 m for a carrier frequency of 100MHz.



a)



b)

Figure 6 a) Geometry of Uniform Linear Antenna, b) Geometry of Uniform Circular Antenna.

4.1.2 Design of a Uniform circular antenna array.

The figure 6 shows the design of a Uniform circular antenna which is made up of N=8 antenna elements arranged in a circular ring of radius *a* and are separated by arc-separation which is equal to half of the wavelength ($\lambda/2$) which is approximately 1.5m. The elements used in the antenna array are simple dipole antennas. The antenna elements are placed on the XY-plane. The carrier frequency used is 100MHz.

CHAPTER 5 RESULTS AND OBSERVATION

5.1 Beam-steering Uniform Linear Antenna Array.

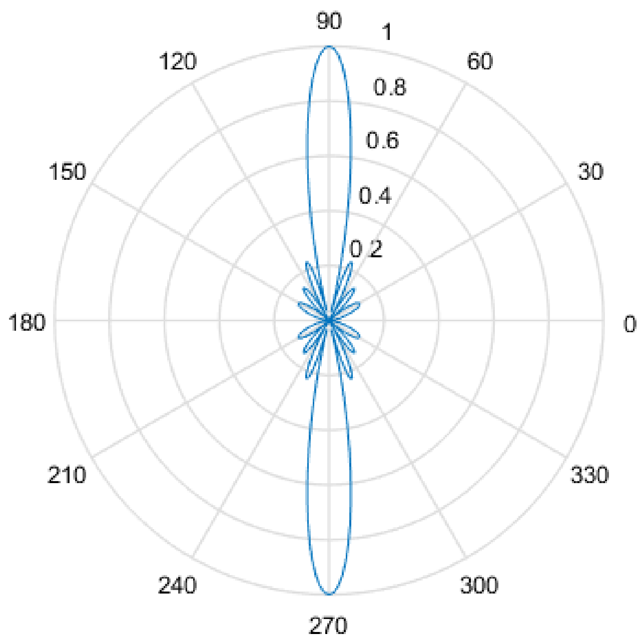
The Uniform Linear antenna array is built as described in the previous section with eight antenna elements. The antenna array was tested for two different values of steer angles, with separation equal to half of the wavelength and consider two values of steering angle being, 90^{o} and another at steer angle of 45^{o}.

5.1.1 Beam-steer towards 90^{o}.

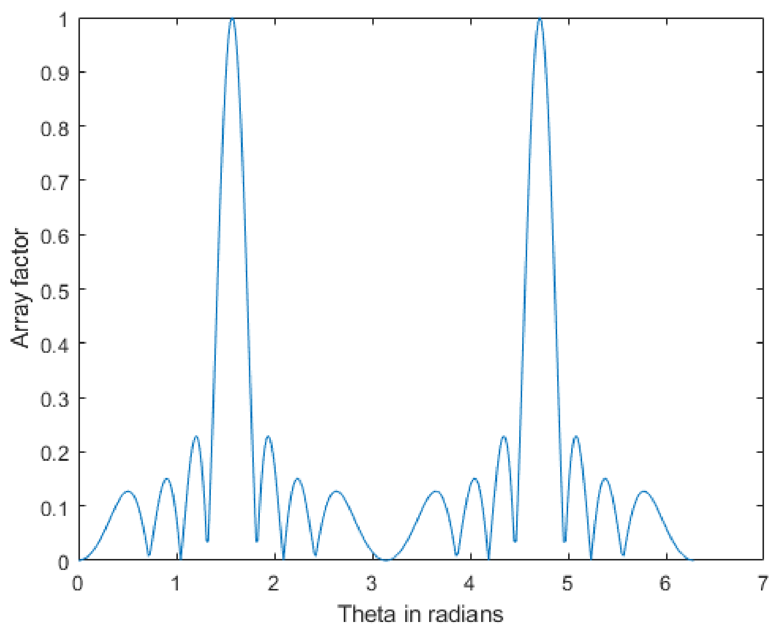
For the Beam to be steered at 90^{o}, the phase delay for each of the antenna element is calculated and the phase of each antenna element is noted as shown in figure 7. The antenna elements, in this case, are considered to have a uniform Amplitude of having the same amplitude which is specified in the vector A in figure 7. Here, each antenna has a different phase due to which the signals undergo constructive and destructive interference and help in directing the signal at constructive interference to the desired direction as shown in figure 8 for both polar coordinate system and Rectangular coordinate system as a 2D plot.

A	[1,1,1,1,1,1,1,1]
c	300000000
d	1.5000
delta	1.5389e-15
deltaAll	*1x361 double*
deltatheta	*1x361 double*
ds	0.1000
dt	2.8571e-10
dtheta	0.0175
f1	*1x1 Figure*
Fa	*1x361 double*
freq	100000000
i	7
k	2.0944
kk	*1x1 Line*
lambda	3
N	8
Ns	30
Nt	35
Ntheta	360
omega	6.2832e+08
R	*1x241 double*
t	*1x36 double*
T	1.0000e-08
temp	*1x361 complex double*
theta	*1x361 double*
valueOfdelta	[1.9237e-16,3.8473e-16,5.7710e-16,7.6947e-16,9.6184e-16,1.1542e-15,1.3466e-15,1.5389e-15]

Figure 7 Values of the parameters used to steer the beam to 90^{o}(Valueofdelta stores the phase of each antenna elements in radians)



a)



b)

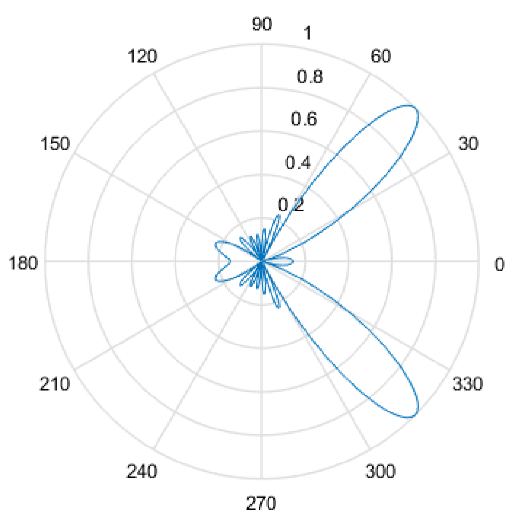
Figure 8 Beam-steered towards 90° shown as a 2D plot in both a) polar coordinate system and b) Rectangular coordinate system.

5.1.2 Beam-steer towards 45°.

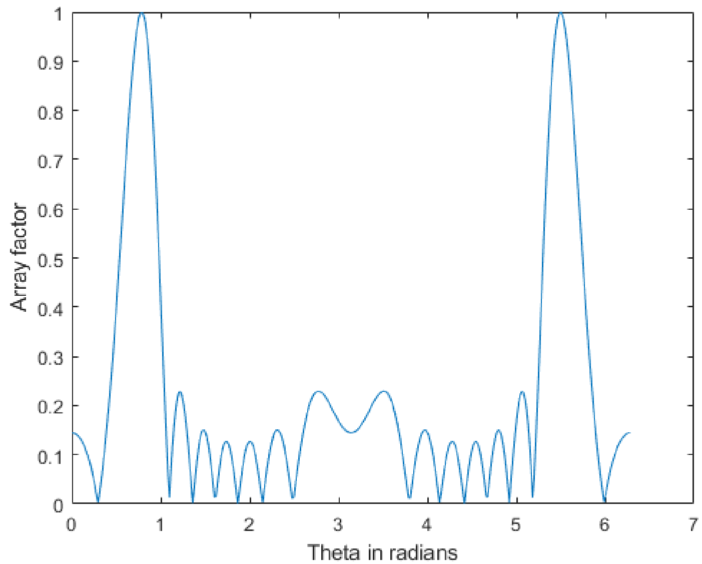
For the Beam to be steered at 45°, the phase delay for each of the antenna element is calculated and the phase of each antenna element is noted as shown in figure 9. Thus, each antenna has a different phase due to which the signals undergo constructive and destructive interference and help in directing the signal at constructive interference to the desired direction as shown in figure 10 for both polar coordinate system and Rectangular coordinate system as a 2D plot.

A	[1,1,1,1,1,1,1,1]
c	300000000
d	1.5000
delta	17.7715
deltaAll	1x361 double
deltatheta	1x361 double
ds	0.1000
dt	2.8571e-10
dtheta	0.0175
f1	1x1 Figure
Fa	1x361 double
freq	100000000
i	7
k	2.0944
kk	1x1 Line
lambda	3
N	8
Ns	30
Nt	35
Ntheta	360
omega	6.2832e+08
R	1x241 double
t	1x36 double
T	1.0000e-08
temp	1x361 complex double
theta	1x361 double
valueOfdelta	[2.2214,4.4429,6.6643,8.8858,11.1072,13.3286,15.5501,17.7715]

Figure 9 Values of the parameters used to steer the beam to 45°(Valueofdelta stores the phase of each antenna elements in radians)



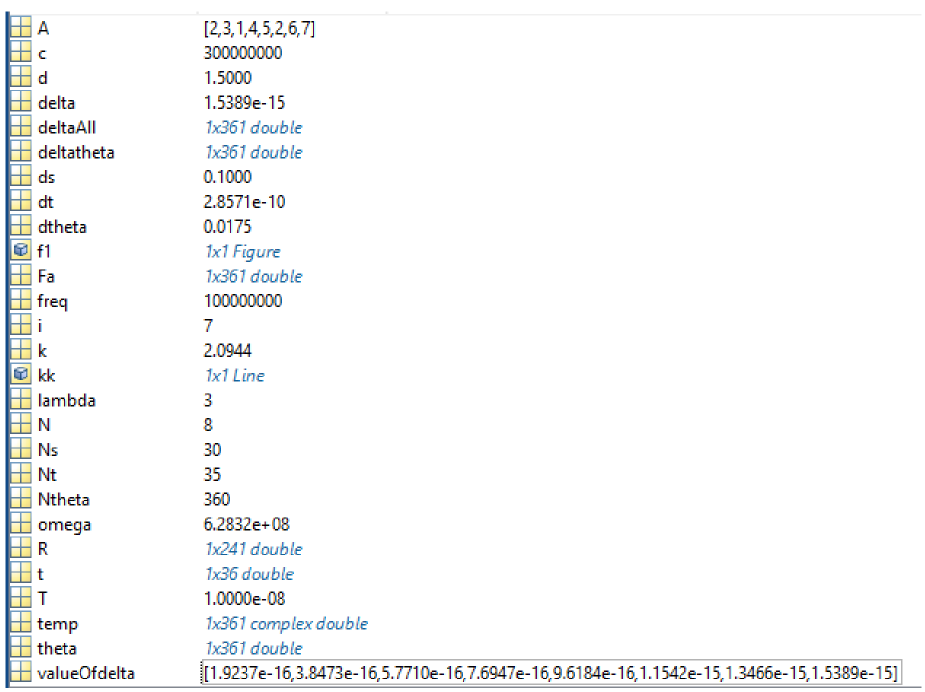
a)



b)

Figure 10 Beam-steered towards 45ᵒ shown as a 2D plot in both a) polar coordinate system and b) Rectangular coordinate system.

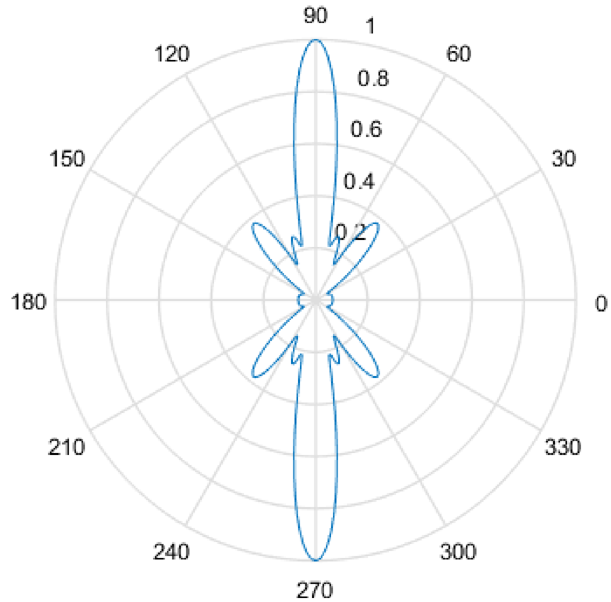
Now considering the Non-uniform amplitude of we change the Amplitude of the antenna elements to be different from each other as shown in figure 11 by vector A.



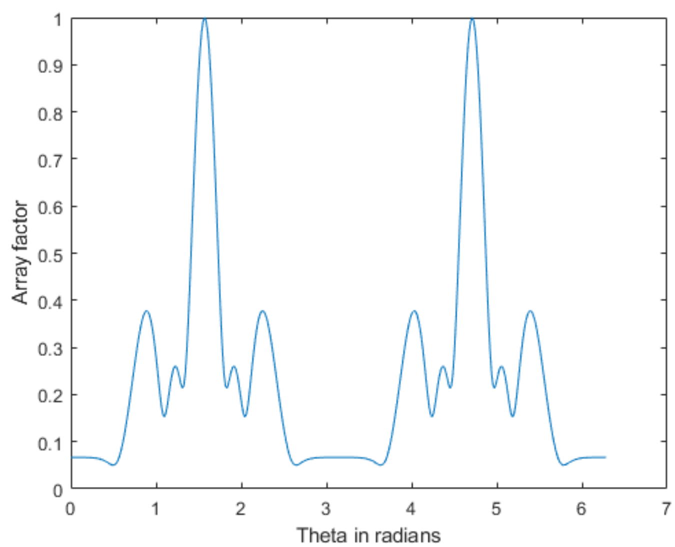
A	[2,3,1,4,5,2,6,7]
c	300000000
d	1.5000
delta	1.5389e-15
deltaAll	1x361 double
deltatheta	1x361 double
ds	0.1000
dt	2.8571e-10
dtheta	0.0175
f1	1x1 Figure
Fa	1x361 double
freq	100000000
i	7
k	2.0944
kk	1x1 Line
lambda	3
N	8
Ns	30
Nt	35
Ntheta	360
omega	6.2832e+08
R	1x241 double
t	1x36 double
T	1.0000e-08
temp	1x361 complex double
theta	1x361 double
valueOfdelta	[1.9237e-16,3.8473e-16,5.7710e-16,7.6947e-16,9.6184e-16,1.1542e-15,1.3466e-15,1.5389e-15]

Figure 11 Values of the parameters used to steer the beam to 90ᵒ for Non-uniform amplitude.

This is done for both the steer angles of 90ᵒ and 45ᵒ and the results of the Beam steered to the desired direction for both the angles are shown in the figure 12a) (polar coordinate system),12b)(Rectangular coordinate system) for 90ᵉ steer angle and the figure 13a)(polar coordinate system),13b)(Rectangular coordinate system) for steer angle of 45ᵉ respectively.

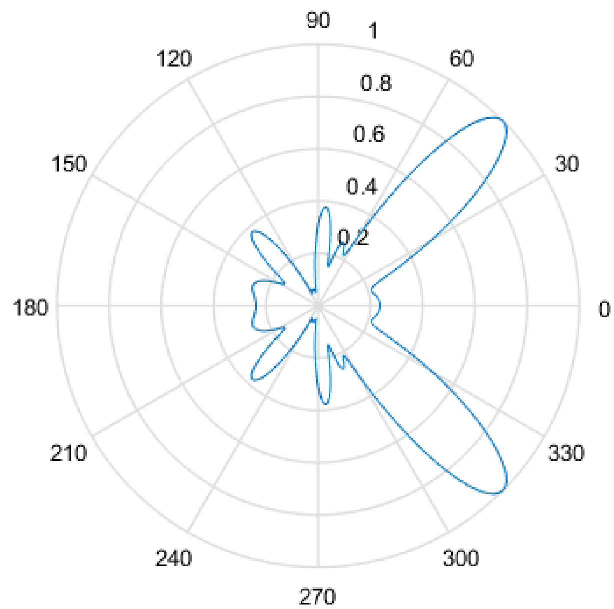


a)

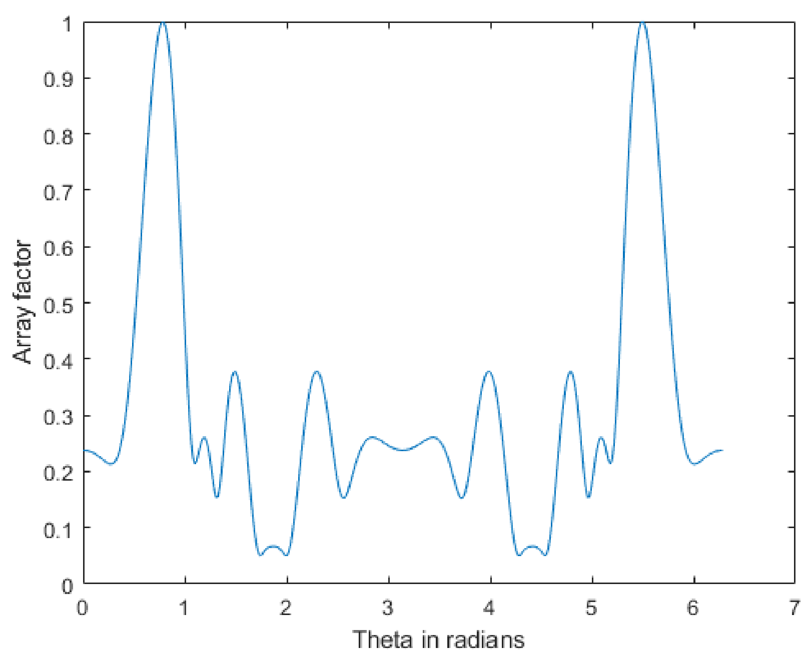


b)

Figure 12 Beam-steered towards 90ᵉ with Non-uniform amplitude shown as a 2D plot in both a) polar coordinate system and b) Rectangular coordinate system.



a)



b)

Figure 13 Beam-steered towards 45º with N0n-uniform Amplitude shown as a 2D plot in both

a) polar coordinate system and b) Rectangular coordinate system.

So, by comparing the plots for Uniform Amplitude antenna array and Non-Uniform Amplitude Array it can be concluded that the Amplitude has only the impact on the magnitude of array factor but does not affect the Beam from steering to the desired direction.

5.2 Beam-steering for Uniform circular Antenna Array.

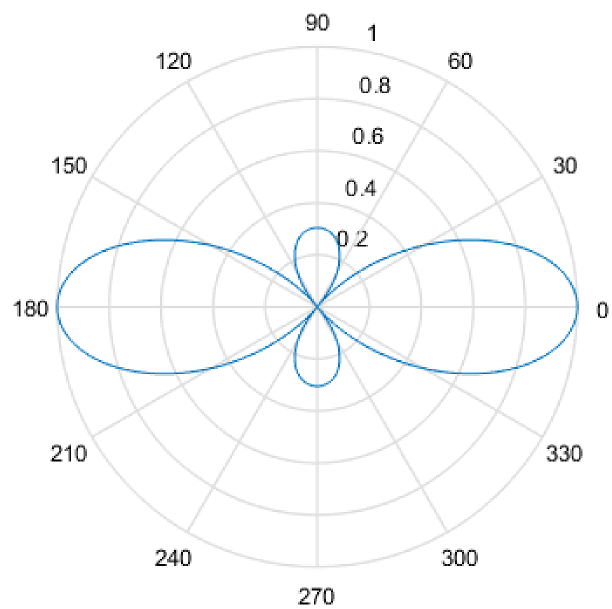
The Uniform circular antenna array is built as described in the previous design section with eight antenna elements. The antenna array was tested for two different values of steer angles, with separation equal to half of the wavelength.Unlike Uniform linear Antenna array the Array factor of the Uniform circular antenna array depends on both Angle of Azimuth (θ) and Angle of Elevation (Φ). So we consider not the single value for the steering angle but a pair of values namely (θ, Φ).The first steer angle Value pair is (180°,0°) and another being (45°,30°).

5.2.1 Beam-steered towards (180°,0°).

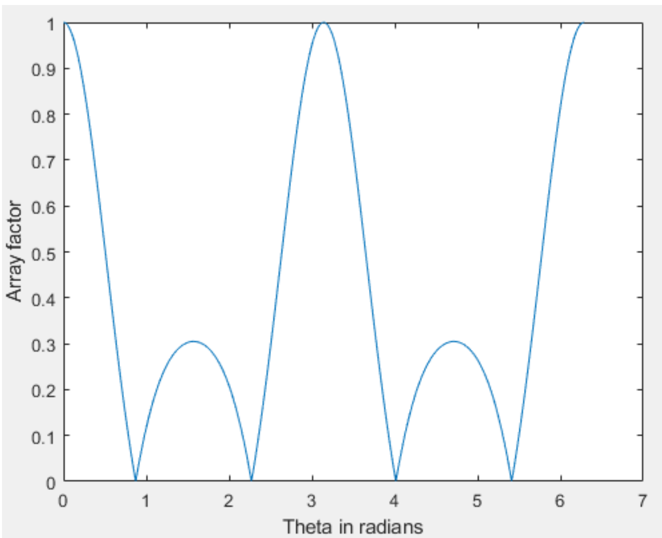
For the Beam to be steered at (180°,0°)., the phase delay for each of the antenna element is calculated and the phase of each antenna element is noted as shown in figure 14. Thus, each antenna has a different phase due to which the signals undergo constructive and destructive interference and help in directing the signal at constructive interference to the desired direction as shown in figure 15 for both polar coordinate system and Rectangular coordinate system as a 2D plot. Here the Angle of Azimuth is considered to be 180° (angle with respect to the y-axis) and Angle of Elevation is considered to be 0°(angle with respect to the x-axis).

a	1.5000
A	[1,1,1,1,1,1,1,1]
c	300000000
delta	-4.8733e-16
ds	0.1000
dt	2.8571e-10
dtheta	0.0175
f1	*1x1 Figure*
Fa	*1x361 double*
freq	100000000
i	7
k	2.0944
kk	*1x1 Line*
lambda	3
N	8
Ns	30
Nt	35
Ntheta	360
omega	6.2832e+08
phi	1.0472
R	*1x241 double*
t	*1x36 double*
T	1.0000e-08
temp	*1x361 complex double*
theta	*1x361 double*
theta_degree	*1x20627 double*
valueOfdelta	[-3.4459e-16,-2.9840e-32,3.4459e-16,4.8733e-16,3.4459e-16,8.9521e-32,-3.4459e-16,-4.8733e-16]

Figure 14 Values of the parameters used to steer the beam to (180°,0°). (Valueofdelta stores the phase of each antenna elements in radians)



a)



b)

Figure 15 Beam-steered towards (180ᵒ,0ᵒ). shown as a 2D plot in both a) polar coordinate system and b) Rectangular coordinate system.

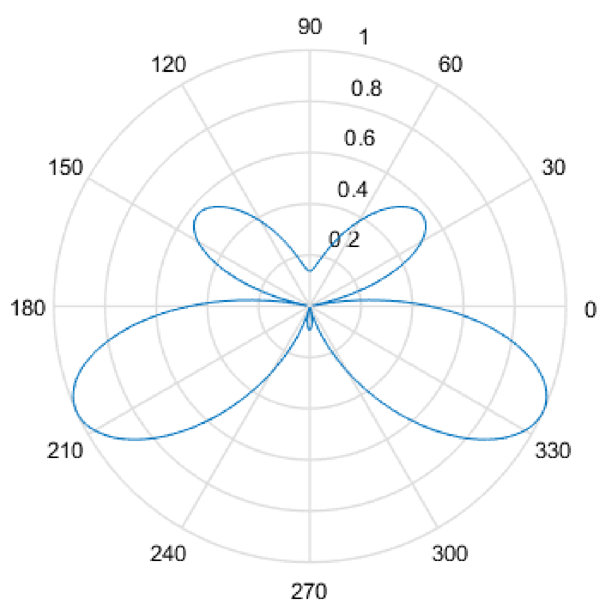
5.2.2 Beam-steered towards (45ᵒ,30ᵒ).

For the Beam to be steered at (45ᵒ,30ᵒ)., the phase delay for each of the antenna element is calculated and the phase of each antenna element is noted as shown in figure 16. Thus, each antenna has a different phase due to which the signals undergo constructive and destructive interference and help in directing the signal at constructive interference to the desired direction as shown in figure 17 for both polar coordinate system and Rectangular coordinate system as a 2D plot. Here the Angle of

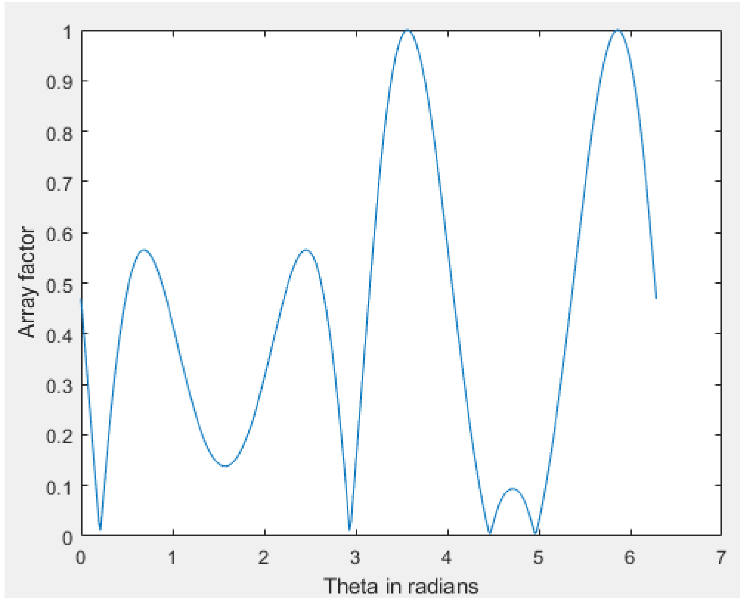
Azimuth is considered to be 45° (angle with respect to the y-axis) and Angle of Elevation is considered to be 30°(angle with respect to the x-axis).

a	1.5000
A	[1,1,1,1,1,1,1,1]
c	300000000
delta	-1.4069
ds	0.1000
dt	2.8571e-10
dtheta	0.0175
f1	1x1 Figure
Fa	1x361 double
freq	100000000
i	7
k	2.0944
kk	1x1 Line
lambda	3
N	8
Ns	30
Nt	35
Ntheta	360
omega	6.2832e+08
phi	1.0472
R	1x241 double
t	1x36 double
T	1.0000e-08
temp	1x361 complex double
theta	1x361 double
theta_degree	1x20627 double
valueOfdelta	[-2.7179,-2.4368,-0.7283,1.4069,2.7179,2.4368,0.7283,-1.4069]

Figure 16 Values of the parameters used to steer the beam to (45°,30°). (Valueofdelta stores the phase of each antenna elements in radians)



a)



b)

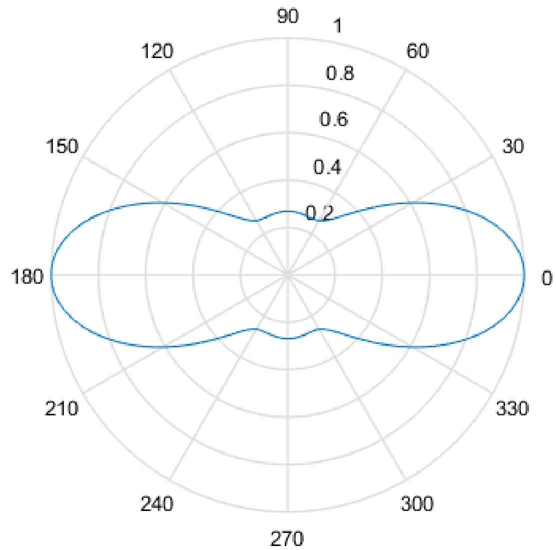
Figure 17 Beam-steered towards (45º,30º). shown as a 2D plot in both a) polar coordinate system and b) Rectangular coordinate system.

Now considering the Non-uniform amplitude of we change the Amplitude of the antenna elements to be different from each other as shown in figure 18 by vector A.

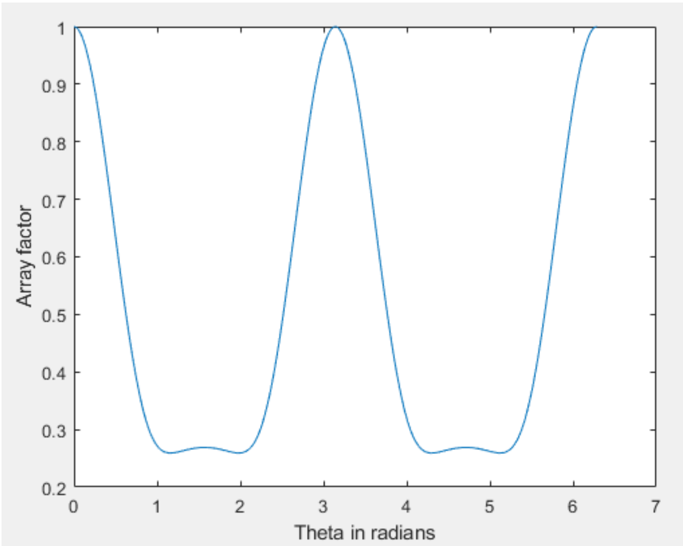
a	1.5000
A	[2,3,1,4,5,2,6,7]
c	300000000
delta	-1.4069
ds	0.1000
dt	2.8571e-10
dtheta	0.0175
f1	1x1 Figure
Fa	1x361 double
freq	100000000
i	7
k	2.0944
kk	1x1 Line
lambda	3
N	8
Ns	30
Nt	35
Ntheta	360
omega	6.2832e+08
phi	1.0472
R	1x241 double
t	1x36 double
T	1.0000e-08
temp	1x361 complex double
theta	1x361 double
theta_degree	1x20627 double
valueOfdelta	[-2.7179,-2.4368,-0.7283,1.4069,2.7179,2.4368,0.7283,-1.4069]

Figure 18 Values of the parameters used to steer the beam to (180º,0º) for Non-uniform amplitude.

This is done for both the steer angles of (180°,0°) and (45°,30°), the results of the Beam steered to the desired direction for both the angles are shown in the figure 19a)(polar coordinate system),19b)(Rectangular coordinate system) for (90°,0°) steer angle and the figure 20a)(polar coordinate system),20b)(Rectangular coordinate system) for steer angle of (45°,30°) respectively.

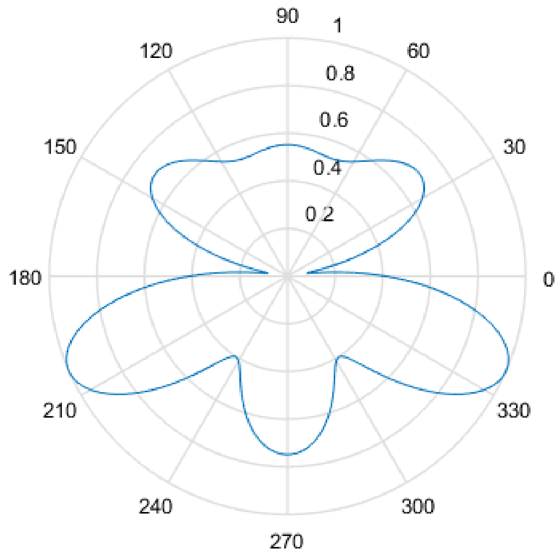


a)

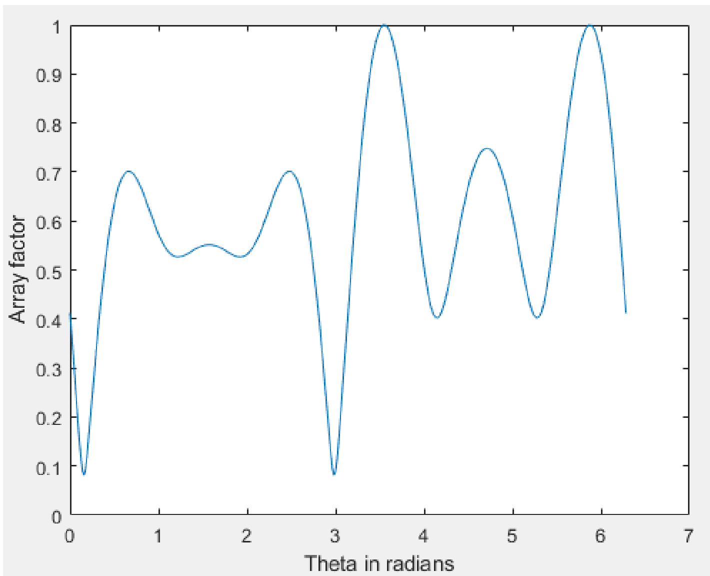


b)

Figure 19 Beam-steered towards (180°,0°) with Non-uniform amplitude shown as a 2D plot in both a) polar coordinate system and b) Rectangular coordinate system.



a)



b)

Figure 20 Beam-steered towards (45º,30º) with Non-uniform Amplitude shown as a 2D plot in both a) polar coordinate system and b) Rectangular coordinate system.

So, by comparing the plots for Uniform Amplitude antenna array and Non-Uniform Amplitude Array it can be concluded that the Amplitude has only the impact on the magnitude of array factor but does not affect the Beam from steering to the desired direction.

CHAPTER 6 HARDWARE IMPLEMENTATION

The Components and the devices used in the Experiment are

1. NI Universal Software Radio Peripheral (USRP) with radio serial number as '30A3E04'.
2. A-INFOMW Broadband Horn Antenna P/N: JXTXLB-1080-M and S/N: J2031090706002.(Receiver).
3. Spectrum Analyzer.
4. PC(Host computer).

The experimental Hardware setup is connected as shown in figure 21 which has An Antenna array with two antenna elements are used as a transmitter and a single Horn antenna is used at the Receiver end. The two signals that are in Quadrature are generated with the same frequency and equal amplitude using NI Universal Software Radio Peripheral (USRP).

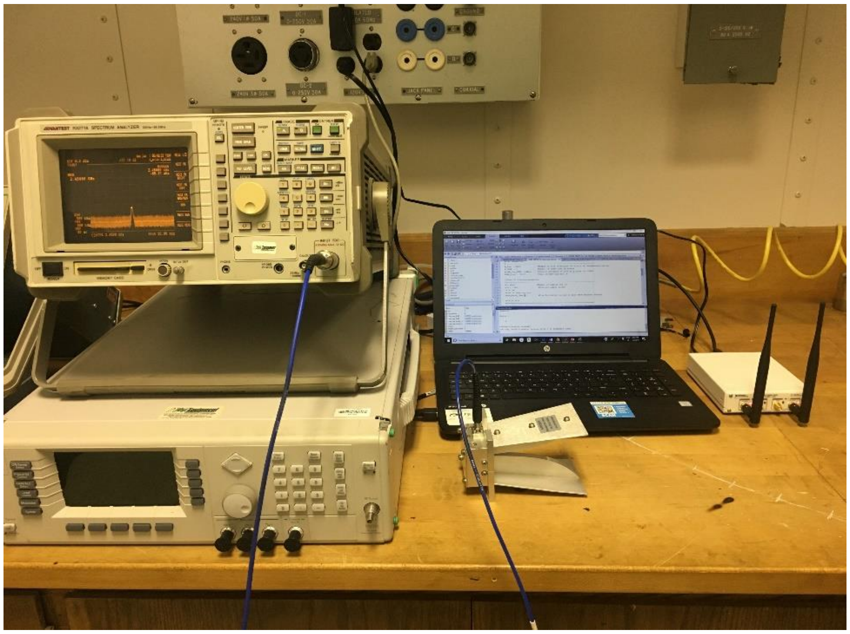
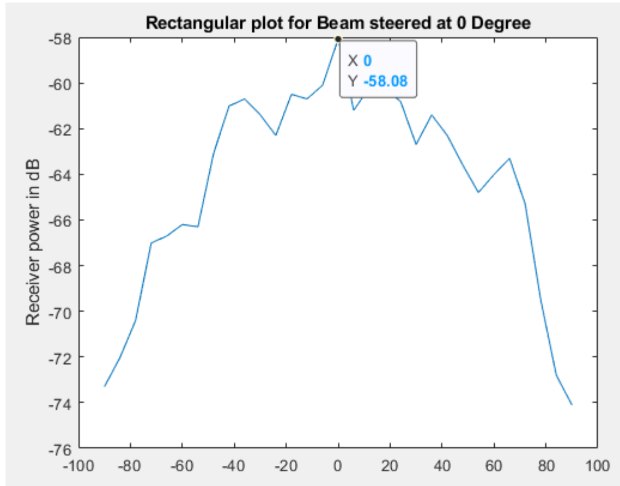


Figure 21 Experimental set up for Beam-steering.

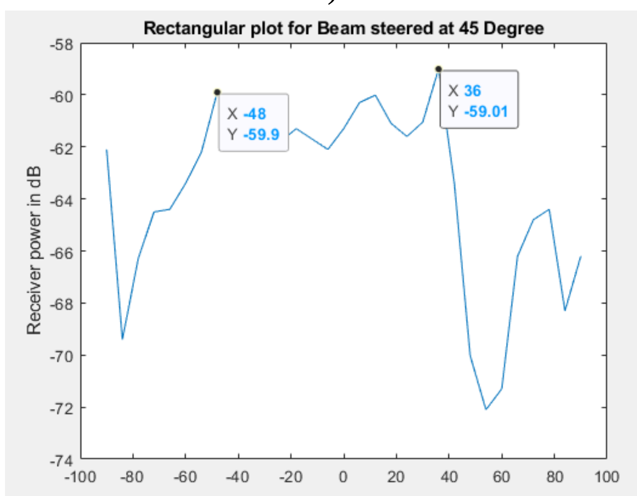
The Power at the Receiver end is determined using the Spectrum analyzer when the phase difference is introduced between the two signals at the transmitter end. Now the power at the receiver which is placed at different points (or angles) on the perimeter of a semicircle at a different instance of time is determined by spectrum analyzer and tabulated in Table 1. This process is repeated for several phase difference to steering the beam towards several directions like 0°,45° and 90° respectively. This Phase for the antenna array corresponding to the steering angle is calculated using the equation 2.15 and that phase is given to the Transmitted signal from the Radio signal Then plot the receiver power versus the angle shows that the beam is steered to the desired direction just by changing the phase of the signals we can change the direction of the beam pattern to the desired direction as shown in the figure 22 a) b) and c).

Table 1 Receiver power at different values of phase Difference.

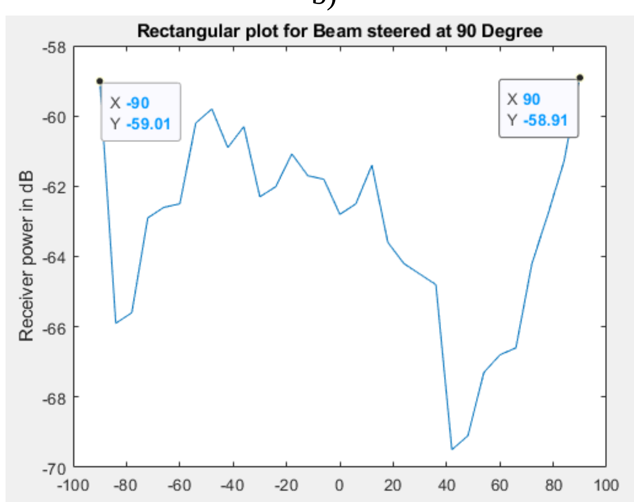
Points on The perimeter of a semicircle around TX	The angle of Rx to Tx in Degree	Receiver Power at 0ᵉ steer angle in dB	Receiver Power at 45ᵉ steer angle in dB	Receiver Power at 90ᵉ steer angle in dB
0	90	-74.1	-66.2	-63.1
1	84	-72.8	-68.3	-63.3
2	78	-69.5	-64.4	-63.8
3	72	-65.3	-64.8	-64.2
4	66	-63.3	-66.2	-67.6
5	60	-64.01	-71.3	-69.4
6	54	-64.8	-72.1	-67.3
7	48	-63.6	-70.02	-69.1
8	42	-62.3	-63.4	-69.5
9	36	-61.4	-59.01	-64.8
10	30	-62.7	-60.05	-64.5
11	24	-60.8	-61.6	-64.2
12	18	-60.3	-61.1	-63.6
13	12	-60.2	-60.01	-61.4
14	6	-61.2	-60.3	-62.5
15	0	-58.08	-61.3	-62.8
16	-6	-60.1	-62.1	-61.8
17	-12	-60.7	-61.7	-61.7
18	-18	-60.5	-61.3	-61.08
19	-24	-62.3	-61.8	-62.01
20	-30	-61.4	-61.4	-62.3
21	-36	-60.7	-60.1	-60.3
22	-42	-61.01	-61.1	-59.9
23	-48	-63.1	-60.9	-59.8
24	-54	-66.3	-62.2	-60.2
25	-60	-66.2	-63.4	-62.5
26	-66	-66.7	-64.4	-62.6
27	-72	-67.01	-64.5	-62.9
28	-78	-70.4	-66.3	-65.6
29	-84	-72.02	-69.4	-65.9
30	-90	-73.3	-62.1	-59.01


Rectangular plot for Beam steered at 0 Degree
Receiver power in dB
X 0
Y -58.08
-58
-60
-62
-64
-66
-68
-70
-72
-74
-76
-100 -80 -60 -40 -20 0 20 40 60 80 100

a)


Rectangular plot for Beam steered at 45 Degree
Receiver power in dB
X -48
Y -59.9
X 36
Y -59.01
-58
-60
-62
-64
-66
-68
-70
-72
-74
-100 -80 -60 -40 -20 0 20 40 60 80 100

b)


Rectangular plot for Beam steered at 90 Degree
Receiver power in dB
X -90
Y -59.01
X 90
Y -58.91
-58
-60
-62
-64
-66
-68
-70
-100 -80 -60 -40 -20 0 20 40 60 80 100

c)

Figure 22 Rectangular 2D plot showing Beam steered in the desired direction a) 0° b) 45° and c) 90°.

CHAPTER 7 MIXER AS A PHASE DETECTOR

The Beam Patterns that are obtained in the previous section depends on the phase and amplitude of the signals that arrive at the antenna ends connected to the radio. In many cases radios have good control over the phase and amplitude at their output but, the jumper cables used to connect the radio with the antenna does not have control over the phase. Some of their long lengths may also lead to temperature variation [10]. So, such an un-controlled phase may lead to the increase the effect of nulls in the Beam Pattern in a way disturbing the main antenna beam. So, a solution to this problem could be to calibrate the phase and Amplitude. In this project, the main concern was the calibration of the phase [10]. Before Calibrating the phase is important to determine the phase shift between the signals from the radio to the signal reached at the antenna end. This Phase detection is done using Mixer in this project.

Most frameworks which require phase data use mixers someplace in the estimation or examination of the phase data. Hypothetically, any mixer with a dc coupled port could be utilized as a phase detector. However, in practice, the mixers have few non-ideal characteristics that may affect the phase detection. Thus, the care must be taken when selecting a mixer used in phase detection by carefully analyzing their non-ideal characteristics [8].

The basic idea behind the phase detector is that when two similar signals of equal frequency and amplitude are given to the mixer then its output is a dc and is proportionate to the difference in phase between the two input signals. Here we are using a double balanced mixer with four diodes whose schematic is as shown in figure 23[8].

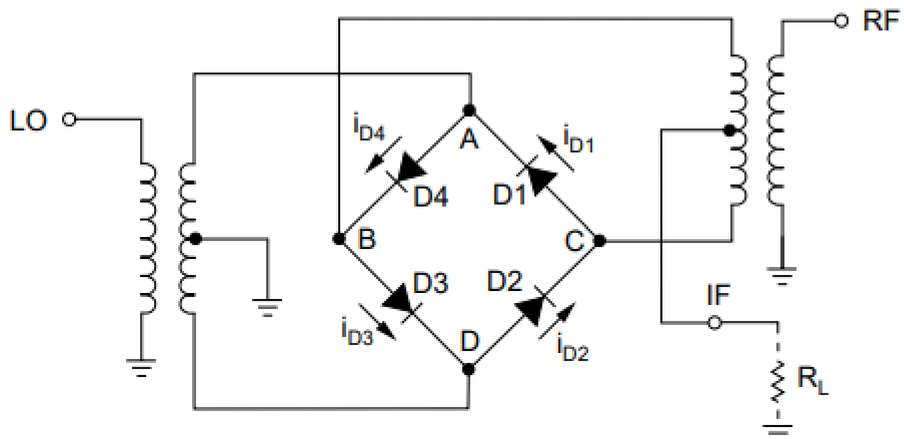


Figure 23 Schematic of a Double balanced Four Diode mixer [8].

The current flowing through the diodes D1, D2 or D3, D4 due to the voltage present at the secondary of transformer LO that depends on the polarity. A dc voltage is seen at points B or C is at ground virtually due to the division of voltage by conduction diode pair. These pair of diodes (D1, D2, and D3, D4) conducts alternatively which makes the voltage at secondary of the RF transformer(B and C) to ground level alternatively, Diode pairs also switch at a rate that is equal to input signal frequency at LO. Thus, we draw that the instantaneous voltage that is developed at the IF port is found by two of them. Firstly, The polarity and the level of the instantaneous voltage at the secondary of the RF transformer and secondly, which of the secondary terminal is at the ground level at that time. So, the output seen at the IF port is the sum of the difference of the input signal frequencies at LO and RF ports.

7.1 Mathematical expressions to derive the output of the Mixer

Now let us see the mixing process that occurs in the diodes in order to determine the operation that takes place in the mixer. To determine the output voltage that is seen at the IF port fists let us consider the waveform for the conduction of the diodes can be obtained in terms of the phase angle and the local oscillator frequency as shown in the equation 7.1[8].

$$G(\omega_L t + \phi_L) = \sum_{n=-\infty}^{+\infty} g_n \exp\big(jn(\omega_L t + \phi_L)\big) \qquad 7.1$$

Where,

ω_L -LO signal frequency.

ϕ_L – LO signal phase angle.

g_n – constant.

Now when a signal is applied at the RF port then a small voltage is observed across diodes that are expressed as shown in equation 7.2[8].

$$V_{RF}(\omega_R t + \phi_R) = \sum_{M=-\infty}^{+\infty} v_m \exp\big(jm(\omega_R t + \phi_R)\big) \qquad 7.2$$

Thus, the current through the diode is given by the expression 6.3[8].

$$i_D = G(\omega_L t + \phi_L)\, V_{RF}(\omega_R t + \phi_R) \qquad 7.3$$

Substituting 7.1 and 7.2 in 7.3 we have

$$i_D = \sum_{n,m=-\infty}^{+\infty} g_n v_m \exp(j(n(\omega_L t + \phi_L) + m(\omega_R t + \phi_R))) \qquad 7.4$$

So, by considering the total current at the IF port due to the ring of four diodes is expressed as 7.5[8].

$$I_{IF} = \frac{1}{2}(i_{D2} - i_{D1} + i_{D4} - i_{D3}) \qquad 7.5$$

Where,

i_{Dj} – current that flows through diode j.

By combining equations 7.4 and 7.5 we get

$$I_{IF} = -\sum_{n,m}^{+\infty} 2\, g_n v_m \exp(j(n(\omega_L t + \phi_L) + m(\omega_R t + \phi_R))) \qquad 7.6$$

Where, *n,m* -All the odd integers.

All the other terms other than *n* x *m=-1* are unwanted inter-modulation products that are to be filtered or they are attenuated by the IF port's frequency response.

Now considering that the frequency of the signals at LO port and RF port to be the same then the current at the IF port is expressed as in the equation 7.7[8].

$$I_{IF} = -2\, g_{\pm 1}\, v_{R\,\mp 1} \exp(j(n(\pm\omega_L t \mp \omega_R))) \qquad 7.7$$

Considering the Load resistance as R and the above equation 7.7, the output voltage can be expressed as the trigonometric function as shown in equation 7.8.

$$V_{IF} = -2\, R\, g_{\pm 1}\, v_{R\,\mp 1} \cos(\pm\phi_L \mp \phi_R) \qquad 7.8$$

Or

$$V_{IF} = -2\, R\, g_{\pm 1}\, v_{R\,\mp 1} \cos(\Delta\phi + \pi) \qquad 7.9$$

From the above equation 7.9, we can conclude that the output voltage at the IF port varies as a function of the cosine function of the difference in the phase between the signals at the LO port and RF port. The output voltage is zero or dc for the phase difference between the two input signal is equal to the value *nπ/2* for $n=\pm 1, \pm 2$ .... and is either minimum and maximum when the phase difference is $n\pi$ for all $n=0, \pm 1, \pm 2$ ....as shown in figure 24[8].

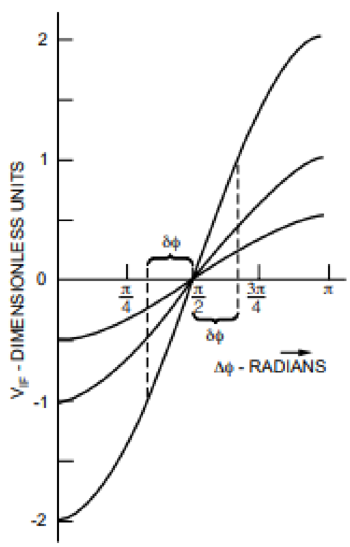


Figure 24 Phase Detector response curve which shows the maximum, minimum and Zero V_{IF} for different phase differences [8].

Now ,After a good understanding on how to determine a phase using Mixer we still have to deal with two problems firstly we obtain a sine wave for the phase detector response curve instead of a sawtooth waveform which creates an ambiguity in phase determination, where we have the same output voltage can have two different phases i.e. one being positive and other being negative. It should be fine if we are just doing the phase-noise testing where we just note the output voltage using two quadrature signals. But when we must determine the phase difference between the signal this data is not enough. Secondly, we must determine the maximum and minimum levels of the output voltage and the DC offset to calculate the phase difference. As we are using the Microlithic mixer the DC offset is very small and can be ignored [9].

So, in order to overcome these problems, we use a Mixer with two Diodes. A best mixer Quadrature hybrid Mixer with two Diodes can be an IQ mixer which can be represented as shown in Figure 25 below.

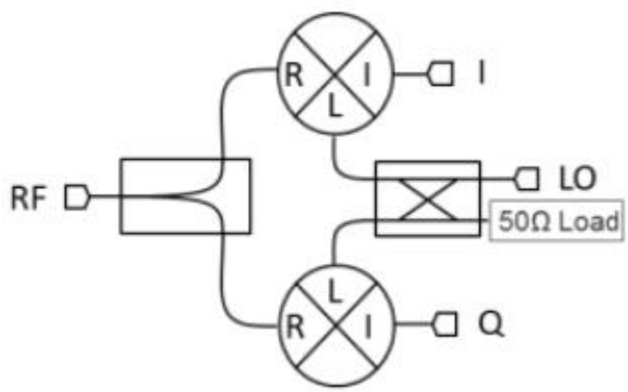


Figure 25 Block Diagram of IQ Mixer [9].

Now as I and Q are Quadrature signals the phase difference between these signals can be found easily by the equation 7.10.

$$\theta = tan^{-1}\left(\frac{v_I}{v_Q}\right) \qquad 7.10$$

Where,

θ- Phase Difference between the two Quadrature signals.

v_I- Voltage at I port.

v_Q-Voltage at Q port.

In this project, we have to use the two signals that are quadrature to each other. These signals are generated using a NI Universal Software Radio Peripheral (USRP) devices programmed using

MATLAB R2018a. The USRP used on a radio platform 'B210' which has a radio serial number as '30A3E04'. This USRP was programmed to transmit two signals with identical frequency and Amplitude but different phases. The mixer used in the experiment is ADL5380. Now one of the signals from USRP is connected to LO of the Mixer and the other signal from USRP to the RF port of the Mixer. These two input signals to LO and Rf ports are given with a different phase difference and the corresponding output voltages at I and Q ports are noted. Now using these output voltages across I and Q (v_I and v_Q) the phase difference between the two signals can be calculated using the above equation 7.10. Table 2 represents the output voltages across I and Q (v_I and v_Q) and the phase difference between the two signals. The Experimental setup for the above phase detection process is as shown in figure 26.

Table 2 Output voltages across I and Q (v_I and v_Q) the Phase difference between the two signals.

Actual Phase difference in Degrees.	v_I in mV	v_Q in mV	Experimental Value of Phase difference (θ) in Degrees.
0	9.1	269.9	1.9
30	20.3	34.8	30.25
60	53.9	37.8	54.95
135	152.1	-154.2	135.3
215	-105.1	-150.9	214.8
300	172.1	-101.4	300.46
350	4.9	-51.1	354.5

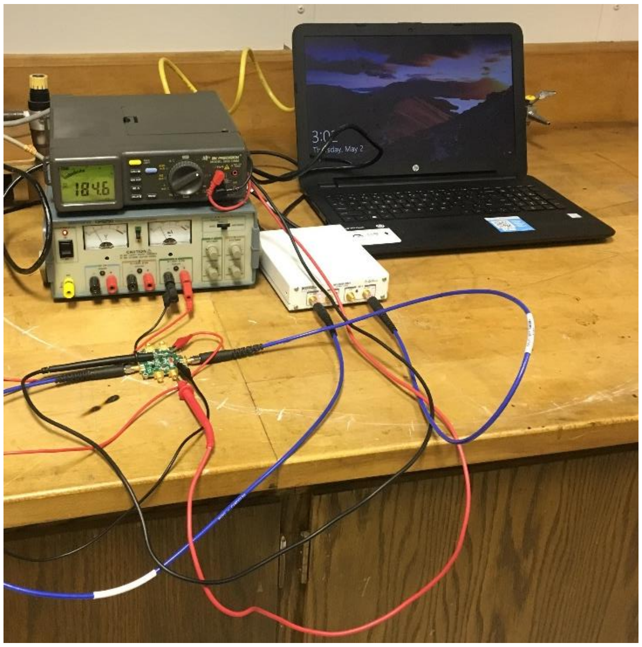


Figure 26 The Hardware setup for Phase detection.

As we can now determine the phase difference between the two signals this could be used to calibrate the phase offset between the antenna and the radio. This Project can further be extended in calibrating the phase using the detected phase.

CHAPTER 8 CONCLUSION

Beamforming and Beam-steering are two connected strategies; however, both are joined into the sorts of antennas that are being used with numerous new correspondences advances like 5G which make increase their demands in this Tech-enthusiastic world for communication.

This Research was mainly to analyze the concepts of Beam steering for the roots and to implement them on the Uniform Antenna Arrays in our case it was ULA and UCA. Both ULA and UCA were programmed using MATLAB and their hardware implementation was done using the NI-USRP at the transmitter end to generate the Input signals to the Transmitter. The results we quite impressive but still not satisfactory. This distraction in the output due to the increase nulls have to lead to the extension of our project where the concept of Calibration was introduced. Knowing the cause of this distorted output Beam Pattern being an uncontrolled phase. So, a solution to this problem could be to calibrate the phase and Amplitude. In this project, the main concern was the calibration of the phase. Before Calibrating the phase it's important to determine the phase shift between the signals from the radio to the signal reached at the antenna end. This Phase detection is done using Mixer in this project. In this project, we were only able to accomplish the task till the phase difference detection and now the future scope of the project lays in the usage of this phase detected as a data to calibrate the un-controlled phase in Future Research work.

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APPENDIX

Code for Beamsteering using Uniform Antenna Arrays

A.UNIFORM LINEAR ANTENNA ARRAY

```
clear all; clc;

%% Simulation parameters
freq = 1e9; % Hz
c = 3e8; % free space speed
lambda = c/freq;
T = 1/freq;
omega = 2*pi*freq;
k = 2*pi/lambda;
N=8;% Number of antenna elements
Ns = 30; % Number of samples per wavelength
ds = lambda/Ns; % Spatial Discretization

Nt = 35; % Number of time samples per period
dt = T/Nt; % Temporal discretization
t = 0:dt:(T); % Duration of simulation: Default is single period
 % Increase the number of periods here for longer simulations
R = (0*lambda):ds:(8*lambda); % Spatial extent
Ntheta = 360; % Number of angular discretization
dtheta = 2*pi/Ntheta;

theta_degree = 0:dtheta:360;
theta = 0:dtheta:(2*pi); % Angular extent of azimuth angle
f1=figure (1);
clf;
set(gcf,'Color',[1 1 1]);
phi=(pi/3);%exitation angle
a= lambda/2;
deltaAll=0:dtheta:2*pi;
%d = lambda/2;
%delta=(pi/180)*88.8;% delta in degrees,for 60degree
steering(delta=k*d*cos(thetanot))
 % detla=-k*a*sin(theta)*cos(phizero-phiN)

for ps=1:length(deltaAll)
    delta=deltaAll(ps);
 A = [1 1 1 1 1 1 1 1]; % Amplitude of each array antenna
 Fa=zeros(1,length(theta));

valueOfdelta = zeros(1,N);
for i=1:(N)
     %phiN=((2*pi*i)/N); angular position of elements,phinot is steering

     delta_new=-k*a*delta*cos((pi/2)-((2*pi*i)/N));

     valueOfdelta(i) = delta_new;
end
 disp(valueOfdelta)
```

```
 a=lambda/2;
 for i=0:N-1
     %phiN=((2*pi*i)/N);
     %delta=((pi/180)*(-k*a*sin(theta)*cos((pi/2)-((2*pi*i)/N)))); %
detla=-k*a*sin(theta)*cos(phizero-phiN)
 temp = A(i+1) .* exp(1j.*(valueOfdelta(i+1)+(k.*a.*(sin(theta).*cos(phi-
(2*pi*i/N))))));

 Fa = Fa + temp;
 end
 Fa=abs(Fa);
 figure(1)
 clf; set(gcf,'Color',[1 1 1]);
 kk=polar(theta,Fa/max(Fa)); hold on; axis off
 set(gcf,'Color',[1 1 1]);
 figure(2)
 xlabel('Theta in radians')
 ylabel('Array factor')
 plot(theta,Fa/max(Fa))
end
```

B. UNIFORM CIRCULAR ANTENNA ARRAY

```
clear all; clc;

%% Simulation parameters
freq = 1e9; % Hz
c = 3e8; % free space speed
lambda = c/freq;
T = 1/freq;
omega = 2*pi*freq;
k = 2*pi/lambda;
N=8;% Number of antenna elements
Ns = 30; % Number of samples per wavelength
ds = lambda/Ns; % Spatial Discretization

Nt = 35; % Number of time samples per period
dt = T/Nt; % Temporal discretization
t = 0:dt:(T); % Duration of simulation: Default is single period
 % Increase the number of periods here for longer simulations
R = (0*lambda):ds:(8*lambda); % Spatial extent
Ntheta = 360; % Number of angular discretization
dtheta = 2*pi/Ntheta;

theta_degree = 0:dtheta:360;
theta = 0:dtheta:(2*pi); % Angular extent of azimuth angle
f1=figure (1);
clf;
set(gcf,'Color',[1 1 1]);
phi=(pi/3);%exitation angle
a= lambda/2;
deltaAll=0:dtheta:2*pi;
%d = lambda/2;
%delta=(pi/180)*88.8;% delta in degrees,for 60degree steering(delta=k*d*cos(thetanot))
```

```
 % detla=-k*a*sin(theta)*cos(phizero-phiN)

for ps=1:length(deltaAll)
   delta=deltaAll(ps);
 A = [1 1 1 1 1 1 1 1]; % Amplitude of each array antenna
 Fa=zeros(1,length(theta));

valueOfdelta = zeros(1,N);
for i=1:(N)
    %phiN=((2*pi*i)/N); angular position of elements,phinot is steering
    %angle exitation
    %delta=-k*a*sin(pi/1)*cos((pi/2)-((2*pi*i)/N)); % detla=-k*a*sin(steerangle(azumith))*cos(phizero-phiN)
    delta_new=-k*a*delta*cos((pi/2)-((2*pi*i)/N));

    valueOfdelta(i) = delta_new;
end
 disp(valueOfdelta)
 a=lambda/2;
 for i=0:N-1
    %phiN=((2*pi*i)/N);
    %delta=((pi/180)*(-k*a*sin(theta)*cos((pi/2)-((2*pi*i)/N)))); % detla=-k*a*sin(theta)*cos(phizero-phiN)
 temp = A(i+1) .* exp(1j.*(valueOfdelta(i+1)+(k.*a.*(sin(theta).*cos(phi-(2*pi*i/N))))));
 %temp = A(i+1) .* exp(1j.*(delta+(k.*a.*(sin(theta).*cos(phi-(2*pi*i/N))))));

 Fa = Fa + temp;
 end
 Fa=abs(Fa);
 figure(1)
 clf; set(gcf,'Color',[1 1 1]);
 kk=polar(theta,Fa/max(Fa)); hold on; axis off
 set(gcf,'Color',[1 1 1]);
 figure(2)
 xlabel('Theta in radians')
 ylabel('Array factor')
 plot(theta,Fa/max(Fa))
end
```

C. CODE TO GENERATE AND TRANSMIT QUADRATURE SIGNALS.

1. %USRP_FMCW_Tx_streaming_main.m

```
%This is the main script used for USRP Tx streaming during FMCW operations.
%It assumes that a single USRP will be used for Tx operations.

%CLEANUP
%============================================================================
clear
clc

%DECLARE VARIABLES
%============================================================================
%USRP parameters
%-----------------------------------------------------------------------------
N_loop = 50e3;            %Number of loop iterations for finite Tx transmission option
N_USRP = 1;               %Number of USRPs used in system
```

```
probe_for_USRP = false;     %Flag to determine to initially probe for USRPs
USRP_type = 'B210';         %Type of USRP used for Tx

%Signal Processing parameters
%--------------------------------------------------------------------------
N = 10e3;                   %Number of samples was 100
n = 0 : N-1;                %Discrete sample points
fs = 1e6;
%Host Tx Sampling rate
show_plots_flag = 1         %flag for whether or not to plot FMCW baseband message

%SCRIPT MAIN
%==========================================================================
disp('Generating FMCW radar baseband message...')
GenFMCWRadarTxMsg               %Generate IQ FMCW Tx data

fprintf('Sampling frequency: %.2e(Hz)\n', fs);
%Save generated FMCW message for future records
disp('Saving Tx FMCW baseband signal...');
save('Tx_FMCW_i.txt', 'x_msg_i1', '-ascii', '-double', '-tabs')
save('Tx_FMCW_q.txt', 'x_msg_q1', '-ascii', '-double', '-tabs')

%Build Tx data to send to Tx USRP object with CH0 being the first column
%and CH1 being the second column.  We are filling in zeros for message sent
%to CH0 and only using CH1.
x_tx_data = [ (x_msg_i1+1j*x_msg_q1)' (x_msg_i2+1j*x_msg_q2)'];



%Show FMCW baseband signal if show_plots_flag is not zero
if(show_plots_flag)
   figure(11)
   plot(1/fs*n, x_msg_i1)
   title('FMCW Message(In-Phase Component)')

   ylabel('Amplitude')
   xlabel('Secs')

   X_MSG_I = fft( x_msg_i1+1j*x_msg_q1);
   figure(4)
   plot(abs(X_MSG_I))
   title('FFT of FMCW message')
end

%Check desired USRP type and instiate appropriate USRP Tx object
if (strcmp(USRP_type,'B210'))
   USRP_Tx_config_and_create_script_B210   %Instantiate X310 USRP Tx object
end

disp('1.Finite transmit and quit')
disp('2.Streaming transmit')
disp('3.EXIT');
choice = input('choice:')

if(choice==1)
```

```
    disp('running one-shot finite transmit')
    USRP_Tx_finite_transmit_dual_channel
elseif(choice==2)
    disp('running streaming transmit')
    USRP_Tx_streaming_transmit_dual_channel
elseif(choice==3)
    disp('exiting...')
else

    disp('invalid choice');

end
disp('Releasing USRP handler object...');
release(radio_tx);
disp('Script terminated successfully');
```

2. %GenFMCWRadarTxMsg.m

```
%This script is used for generating an FMCW message specifically for the
%single Tx USRP FMCW system.

%DECLARING VARIABLES

%==========================================================================
%Tx message signal parameters
%--------------------------------------------------------------------------
T =1;               %Tx power
f_start1 = 1000e3; %was 0.1e6
f_start2 = 1000e3;   %was 0.01e6 to check for Mixing operetion
%f_stop = 2e6;          %Chirp stop frequency
T_chirp = .05e-2;       %Chirp period in seconds-3
%N_delay = 10e3;         %Discrete point delay of pulse
N_pulse = T_chirp*fs;
%Discrete point chirp period
phase1=(0)*(pi/180);
phase2 =0;
%SCRIPT MAIN
%==========================================================================
%Tx message signal generation
%--------------------------------------------------------------------------
fprintf('Generating message signals...\n');
%fprintf('Chirp stop frequency: %.2e(Hz)\n', f_start);
%fprintf('Chirp start frequency: %.2e(Hz)\n', f_stop);
%fprintf('Pulse delay: %.2e(secs)\n',  N_delay/fs);
%fprintf('Pulse width: %.2e(secs)\n', N_pulse/fs);
%k_chirp = (f_stop - f_start)/(N_pulse/fs);      %Chirp slope

chirp_exp_pulse_repeat1 = exp(-1*(1j*(2*pi*(f_start1/fs)*n(1:N) + phase1)));
chirp_exp_pulse_repeat2 = exp(-1*(1j*(2*pi*(f_start2/fs)*n(1:N) + phase2)));
%N_periods1 = floor(N/N_pulse);
%N_periods2 = floor(N/N_pulse);

%chirp_exp_pulse_repeat1 = repmat(chirp_exp_pulse1,1,N_periods1);
%chirp_exp_pulse_repeat2 = repmat(chirp_exp_pulse2,1,N_periods2);
```

```
chirp_exp_full1 = T*[chirp_exp_pulse_repeat1 chirp_exp_pulse_repeat1(1:N-length(chirp_exp_pulse_repeat1))];
chirp_exp_full2 = T*[chirp_exp_pulse_repeat2 chirp_exp_pulse_repeat2(1:N-length(chirp_exp_pulse_repeat2))];
x_msg_i1 = real(chirp_exp_full1);     %Vector to hold message in-phase vector
x_msg_q1 = imag(chirp_exp_full1);   %Vector to hold message quadrature vector

x_msg_i2 = real(chirp_exp_full2);     %Vector to hold message in-phase vector
x_msg_q2 = imag(chirp_exp_full2);   %Vector to hold message quadrature vector
```

3. %USRP_Rx_config_and_create_B210.m

```
%This script is used to create USRP session handlers and configure them.
%Available USRPs are first detected.  A USRP handler is then created and
%configured.
%This script assumes B210-based USRP model is being used

%DEFINE VARIABLES
%===========================================================================
%Rx USRP parameters
%---------------------------------------------------------------------------
radio_platform = 'B210';           %USRP model being used
radio_serial_num = '30A3E04';       %USRP device serial number

radio_address = '';                %String to contain USRP IP addresses
tx_ch_mapping = 1 : 2*N_USRP;       %List of channels for Rx USRP system to use
fc = 2.45e9;%*ones(1,1*N_USRP);     %Carrier frequency(vector form)

tx_gain = 40*ones(1,2*N_USRP);       %USRP Rx port gain(vector form)
tx_clock_src = 'Internal';          %Reference clock source for USRP hardware
tx_master_clock_rate = 8e6;        %USRP onboard clock rate
tx_transport_data_type = 'int16';   %Datatype representation of USRP rx samples
%output_data_type = 'single';       %Datatype of output signal
%N_rx_frame = 10e3;                 %Samples per frame of USRP object output
N_tx_frame = 2.5e3;                 %Highest stable samples/frame for 100MHz host fs



%tx_pps_sync_src = 'Internal';       %Source of USRP system PPS sync signal
enable_burst_mode = 0;

N_burst_frames = 10;             %Highest stable frames/burst for 100MHz host fs and seven USRPs, N_rx_frame =
3e3
N_burst_frames = 16;             %Highest stable frames/burst for 100MHz host fs and eight USRPs, N_rx_frame =
3e3

%---DEBUG---
N_tx_frame = 100;
N_burst_frames = 101;
%---DEBUG---

cfg_timeout = 4;                 %USRP config timeout(in seconds)
%SCRIPT MAIN
%===========================================================================
%Check for connected radios(may not be completely neccessary
if probe_for_USRP
```

```
    disp('checking for connected radios...')
    radio_probe = findsdru();
    if strncmp(radio_probe(1).Status, 'Success', 7)
        disp('USRPs detected(assumming B-series USRP)')
        %radio_found = true;
        %radio_platform = radio_probe(1).Platform;
    else
        error('No radios detected')
    end
end


%Create a single USRP Tx handler for single USB USRP in  Tx system
disp('Generating a single USRP Tx object')
radio_tx = comm.SDRuTransmitter('Platform', radio_platform,...
    'SerialNum', radio_serial_num);

%pause(cfg_timeout);
%Configure USRP Rx handler
disp('Configuring Tx USRP parameters...');
disp('Applying channel mapping...');
radio_tx.ChannelMapping = tx_ch_mapping;
%pause(cfg_timeout);
disp('Applying Tx gain...');
radio_tx.Gain = tx_gain;
disp('Applying clock source...');
radio_tx.ClockSource = tx_clock_src;
disp('Applying master clock rate...');
radio_tx.MasterClockRate = tx_master_clock_rate;
disp('Applying interpolation factor...');
radio_tx.InterpolationFactor = ceil(radio_tx.MasterClockRate/fs);
%disp('Applying output data type...');
radio_tx.TransportDataType = tx_transport_data_type;
%radio_tx.OutputDataType = output_data_type;
% disp('Applying samples per frame...');
% radio_tx.SamplesPerFrame = N_tx_frame;
%disp('Applying PPS source...');
%radio_tx.PPSSource = tx_pps_sync_src;

radio_tx.EnableBurstMode = enable_burst_mode;
if(enable_burst_mode)
   disp('Setting burst mode frame size...');
   radio_tx.NumFramesInBurst = N_burst_frames;
end
```

4. %USRP_Tx_streaming_transmit_dual_channel.m

```
%Collect a finite collection of samples from USRP and then quit

%SCRIPT MAIN
%=======================================================================
disp('Starting finite streaming process (ctrl-c to terminate loop)...')

%Next send data through the Tx USRP object in an indefinite loop
```

```
while(1)
   radio_tx(x_tx_data);    %Send message frames over to USRP
end
```