Mills Cross MIMO Radar Architecture to Improve Angular Accuracy

A project thesis

submitted by

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in partial fulfillment of the requirements
for the award of the degree of

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Certificate

This is to certify that the thesis titled **Mills Cross MIMO Radar Architecture to Improve Angular Accuracy**, submitted by **V S Rama Krishna Anne**, to the Indian Institute of Technology, Madras, for the award of the degree of Master of Technology, is a bonafide record of the research work done by V S Rama Krishna Anne under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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Abstract

Keywords: Mills Cross Array, Ubiquitous Radar, MIMO radar, MIMO waveform

Radar has become an indispensable sensor in both war and peace scenarios. Radars employing traditional techniques like mechanically rotating or electronic scanning have limitations with respect to time on target, which is vital for the SNR and target detection requirements. Currently radar detection capabilities are being improved through the use of higher transmit power. Due to advancements in the hardware capabilities, parallel processing can be employed with minimal power consumption. This advantage paved the way for Ubiquitous Radar concepts.

Ubiquitous radar concepts allow simultaneous and all the time use of resources, which theoretically provides infinite time on target. This calls for additional hardware complexity. The use of traditional Mills Cross which is widely used in the Sonars domain can be adapted to handle the hardware complexity efficiently. Also, MIMO radar architecture has advantages compared to traditional radar architecture. With MIMO, improvement in the angular accuracy can be achieved without expending higher transmit power.

The current thesis explores the possibility of using ubiquitous radar concepts in the Mills cross radar architecture. The proposed architecture proposes the use of MIMO waveform design to improve the angular accuracy. Simulations of the radar processing chain are carried out and concept was proved by resolving the targets in azimuth direction. The proposed architecture and waveforms can be used to resolve the targets in the elevation also. MIMO waveforms in CW domain and pulsed domain are proposed to meet the orthogonality criterion. The designed architecture can be adapted for both small and long-range radars. The work provided software configuration-based mode switching from the surveillance to tracking to achieve a better Probability of Detection.

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Chapter 1

Introduction

1.1 Radar

Radar is an electronic device for the detection and localization of objects. It operates by transmitting a particular type of EM waveform, and detects the reflections from the target as echo signal. Radar can be designed to work under conditions like darkness, haze, fog, rain, snow. In addition, radar has the advantage of being able to measure target parameters range, azimuth, elevations and velocity.

Radar is employed for applications like air surveillance, surface search, tracking and guidance, weather radar, Earth observation. Basic block diagram of radar, shown in Fig. 1.1, consists of a transmitter which radiates electromagnetic wave forms through transmitting antenna. A portion of the transmitted signal reflected by a target and is re-radiated in all directions. The receiving antenna collects the returned energy and fed to receiver, where it is processed to detect the presence of the target and to extract some of its parameters[1].

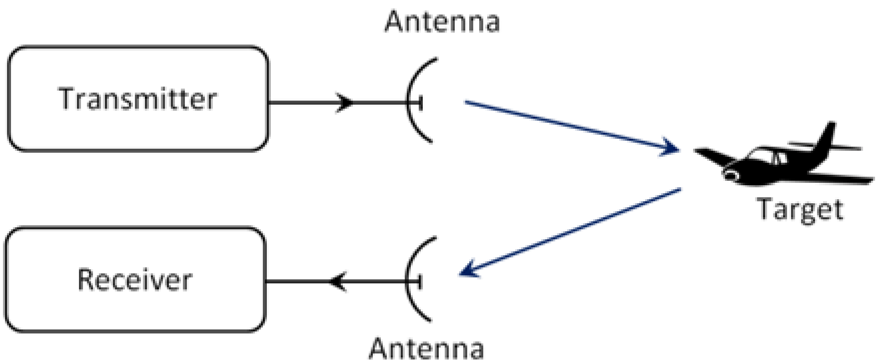

Figure 1.1: Radar Block diagram

1.1.1 Types of Radars

Surveillance Radar[1]

A Surveillance Radar is a sensor that illuminates a large portion of space with an EM waves and receives back the reflected waves from targets. This is primarily used to detect the target presence, target positional information is may not be accurate to neutralize. Here amount of time to scan the area is equally divided to the all the directions. Surveillance radars are can be of 2-D or 3-D.

Tracking Radar[1]

A Tracking Radar is a sensor that closely follows the designated targets, target positional information is accurate. Normally tracking radars obtain the cue from the surveillance radars. After obtaining the cue, the amount of time is fully dedicated to the direction towards target.

Mechanically Scanned Radar[1]

In olden days Radar scans the whole azimuth and elevation through mechanical means. In this narrow beam is formed and rotated to obtain the full picture of the area to be scanned.

Electronically Scanned Radar[1]

These are also called phased array radars. In phased array radars scanning the azimuth and elevation is done thorough electronic means. Narrow beams are shifted by giving certain phase shift to the antenna elements. Breakthrough in the Digital beam forming has paved the way for development of the electronically scanned Radars. Electronically scanned radars beams synthesis and scanning can be simulated in Matlab to verify the scan losses[2]. This Digital beam forming techniques were popular in advanced wireless communications also [3].

1.2 Ubiquitous Radar

A ubiquitous radar is one that present all the time and looks in all intended directions. It does this by using a low gain omni-directional or almost omni-directional transmitting antenna and a receiving antenna that generates a number of contiguous high gain fixed beams. The concept was initially brought by Merill Skolnik in his Naval Research Laboratory report [4]. Even though it was published long back

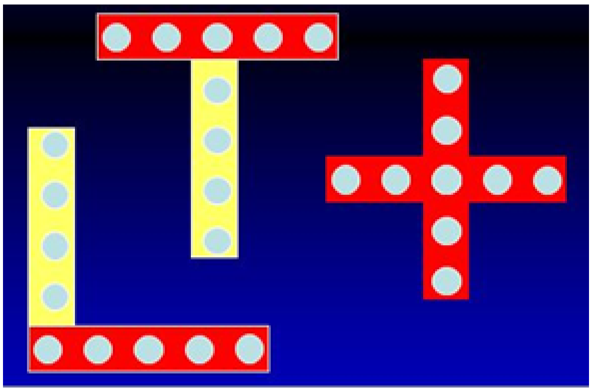

Figure 1.2: Example Mills Cross Architectures

hardware limitations to form multiple beams was the limiting factor to get notified by Radar engineers.

To detect small RCS targets, radars are usually designed for high peak power levels to improve the return peaks energy. Unfortunately radars needs to operate in the presence of strong clutter, resulting in challenging requirements on system dynamic range, stability, isolation, phase noise, spurious and other hardware specifications. Using the Digital Beam forming techniques we can form multiple beams simultaneously through this area to be scanned is illuminated by low gain transmitter [5] [4]. To detect the small objects having less RCS ubiquitous radar has become necessity [6].

1.3 Mills Cross Radar

Mills cross configuration widely used in the Sonar applications [7]. In this configuration, two separate antennas arranged like a “T” or “+” [8], to achieve a compromise between control over the sound beam and technical complexity. One of the antenna is used for transmitting the acoustic signals and the second one is the receiving antenna which can be used to form multiple beams. With this the received signals can be analyzed and a plurality of received beams can be Synthesized.

Similar architecture has become popular for radars in recent days to reduce the power consumption of the active arrays [9]. In this configuration scanning is done only in one direction either Azimuth or elevation. Recently Mills cross radar has become popular in many radar applications to reduce the requirement of receive elements[10].

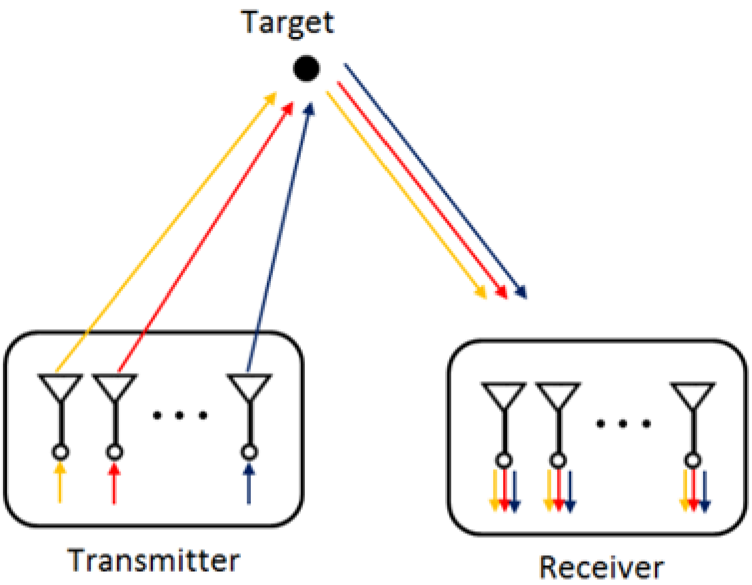

Figure 1.3: Basic MIMO Block diagram

1.4 MIMO Radar

Multiple-input multiple-output (MIMO) radar is phased array radar with digital receivers and orthogonal waveform generators. As shown in Fig 1.3 Multiple transmitters will radiate orthogonal wave forms to improve the diversity. At each receiver matched filter is implemented to extract the transmitted orthogonal codes. The improved diversity can be exploited for better spatial resolution, Doppler resolution, and dynamic range [11].

MIMO radar can be used to obtain low-probability-of-intercept radar properties. In a traditional phased array system to improve the angular accuracy additional antennas and related hardware required, whereas in MIMO this can be achieved with not much additional hardware.

1.5 About Thesis

In this thesis i have conveyed that how MIMO and MILLS cross techniques can be exploited to cover the large area in small scan time. MIMO concepts were used to improve the angular accuracy with the available resources. MIMO concept was used with Sonar and Mills cross architecture to improve the angular accuracy[12]. Similar concept was applied in the Ubiquitous Radar to reduce the scan time and improve the angular accuracy. In chapter 2 detailed the Radar system design aspects, chapter 3 covers the proposed scheme and signal models, chapter 4 covers the results and analysis and will conclude with conclusions and future work in chapter 5

Chapter 2

Radar System Design

Radar is the primary sensor to detect the target presence and notifying the positional information of the target. Range, Azimuth and speed are the main target parameters given by the Radar. Waveform design plays a crucial role in determining the radar capability in Range and speed [1]. Positional information (Azimuth and Elevation) is mainly a function of Antenna design[1]. Due to recent developments in phased arrays and MIMO, positional information can be improved by careful design of both wave forms and antenna together[11]. Before explaining design techniques to improve the positional accuracy basic design considerations also explained in this chapter.

2.1 Radar Range Equation

2.1.1 Surveillance

$$R_{max}^4 = \frac{P_{av} A_e t_s \sigma}{(4\pi)\Omega (S/N)_{min} k T_s L} \tag{2.1}$$

Each parameter of the equation are detailed in table 2.1 [13].

2.1.2 Tracking

$$R_{max}^4 = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 (S/N)_{min} k T_s B_n L} \tag{2.2}$$

Each parameter of the equation are detailed in table 2.2[13].

2.1.3 Design Parameters

Range

As per the radar equation main parameter to be designed in the amount of power to be transmitted. Here we have to finalize the size of the target to be intended also

Table 2.1: Surveillance Radar equation Parameters

R_{max}	Maximum Radar Range
P_{av}	Average Power Transmitted
A_e	Effective Aperture
t_s	Scan time for Ω
σ	Effective Radar Cross Section
Ω	Solid Angle Searched
$(S/N)_{min}$	Minimum S/N to have detection
K	Boltzmann's Constant
T_s	System Noise temperature
L	System Losses

Table 2.2: Tracking Radar equation Parameters

R_{max}	Maximum Radar Range
P_t	Peak Power Transmitted
G	Transmit and Receive Antenna Gain
λ	Operating Wave length
σ	Effective Radar Cross Section
$(S/N)_{min}$	Minimum S/N to have detection
K	Boltzmann's Constant
T_s	System Noise temperature
B_n	Noise Bandwidth of Receiver
L	System Losses

as it effects the reflected energy. After finalizing the power and target we need to finalize the pulse repetition frequency.

Range of the target is mainly determined by measuring the time between the transmitted pulse and reflected pulse [14]. PRF tells the amount of time radar waits to transmit the next pulse. This determines the maximum unambiguous range any radar can be detected as shown in fig 2.1 and 2.2. In the FCW radar the time corresponds to max range is considered for calculating the max beat frequency. In pulsed radars, pulse width duration time is the min range that can be achieved, where as in FMCW radars min range that can be achieved is the function of Tx and Rx antenna coupling. Pulsed radars are mainly used for the long-range applications and FMCW radars for short range applications.

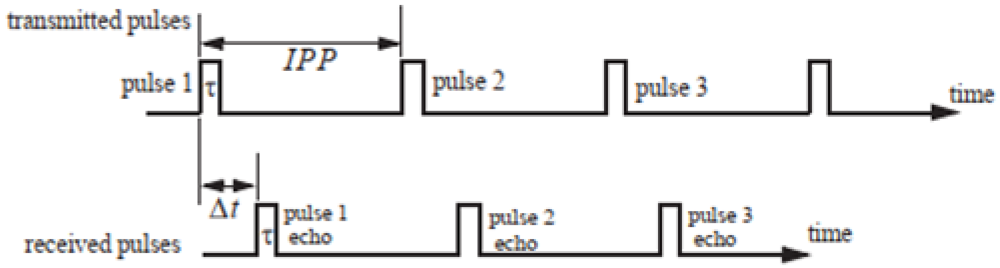

Figure 2.1: Radar Range determination in Pulsed Radars

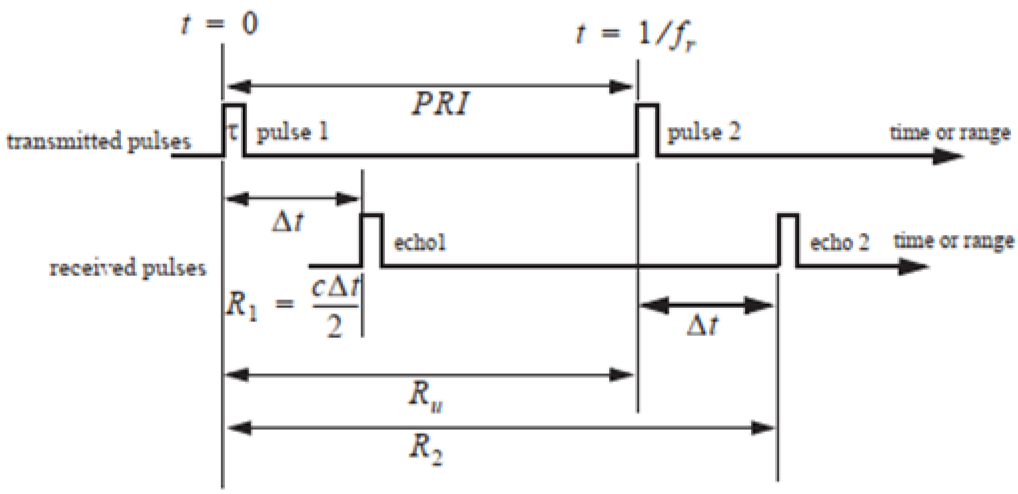

Figure 2.2: Radar Range Ambiguity

Range Resolution

This is the crucial parameter to determine the multiple targets in the range domain. This conveys that minimum separation that targets should maintain do detect as two different targets[14]. This is mainly funtion of system bandwidth. In pulsed radars, pulse width and in FMCW minimum beat frequency we can identify in the frequency domain determines the range resolution capability. If we make the pulse much narrow, the reflected signal energy many not be sufficient so techniques like pulse compression can be employed to improve the range resolution are available with large pulse width.

Speed

Speed of the target can be detected by extracting the frequency shift in the reflected pulse[14]. Any target which is moving either towards or away from the radar induces a doppler shift in the echo. This doppler shift can be extracted to identify the speed of the target. Doppler resolution is the inverse of the time on target, i.e observation time of the measurement.

Azimuth Resolution

In a radio antenna pattern, the Azimuth beam width is the angle between the half-power (-3 dB) points of the main lobe in Azimuth direction[14]. It is a function of the antenna aperture dimension in Azimuth plane. Bigger the aperture in Azimuth direction narrower the beam in Azimuth direction. Azimuth resolution is the minimum separation between the two targets in Azimuth plane.

Elevation Resolution

In a radio antenna pattern, the Elevation beam width is the angle between the half-power (-3 dB) points of the main lobe in Elevation plane[14]. It is a function of the antenna aperture dimension in Elevation plane. Bigger the aperture in Elevation direction narrower the beam in Elevation direction. Azimuth resolution is the minimum separation between the two targets in Azimuth plane.

Antenna Gain

It's a function of the both Azimuth beam width and Elevation Beam width [14]. Antenna gain is inversely proportional to the Azimuth and Elevation beam widths. We can achieve higher gains in the antenna if we increase the aperture size of the antenna in both Azimuth and Elevation planes.

2.2 Summary

So, from the above radar parameters we can decide that to get the accurate positional information of the target we should design both waveform and antennas to be designed carefully. To improve the angular accuracy large aperture antennas are required [15]. In this thesis to improve the angular accuracies by designing the antenna and waveforms together is explained in the chapter 3.

Chapter 3

Proposed Scheme

In order to scan the huge area in less scan time with sufficient time on target it was proposed to use the Mills cross radar with ubiquitous Radar concepts[4][8]. In these two linear arrays which are orthogonal to each other were used to cover azimuth and elevation space of the scan area. By employing the Mills cross the antenna elements requirement has come down drastically [12]. With the help of ubiquitous radar concepts, we could achieve the large time on target with the less transmitted power. Finally, by using more transmitters which are radiating orthogonal waveforms virtual arrays are formed and improved the angular accuracies in both Azimuth and Elevation planes [16]. In this chapter initially i will present the signal model for the Mills Cross Sonar and adapt the similar model for the Mills Cross Radar.

3.1 Signal Model

3.1.1 Mills Cross Sonar

The Mills Cross Radar is used for the sea surveillance, in this one transmit array and receive array positioned orthogonal to each other[8]. In the Mills Cross array all the transmitter elements radiate coherent this coherent signal is spatially combined in desired direction and reflections from this signal is sampled by the receiver. Receive Linear array forms multiple beams in search area. In order to improve the angular accuracies it was proposed to use MIMO concepts in the Mills Cross Sonar[12]. Here in the transmit array will radiate orthogonal waveforms, these can't be coherently combined in the space. In the paper author used 'T' type of Mills cross radar as referred in fig 3.1. Here transmitter and receiver arrays can be of sub arrays also, that means some of the elements can be combined and made as Sub arrays as shown in fig 3.2.

To maximize the transmit power all the elements in the sub array can be weighted with the following vector $\bar{w}$ in eqution 3.1 at a elevation angle θ_0. Here f is the

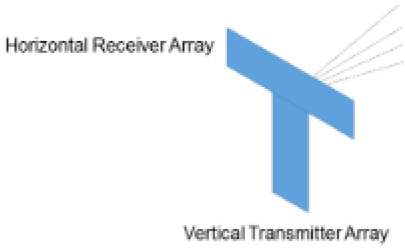

Figure 3.1: Mills Cross in Sonar

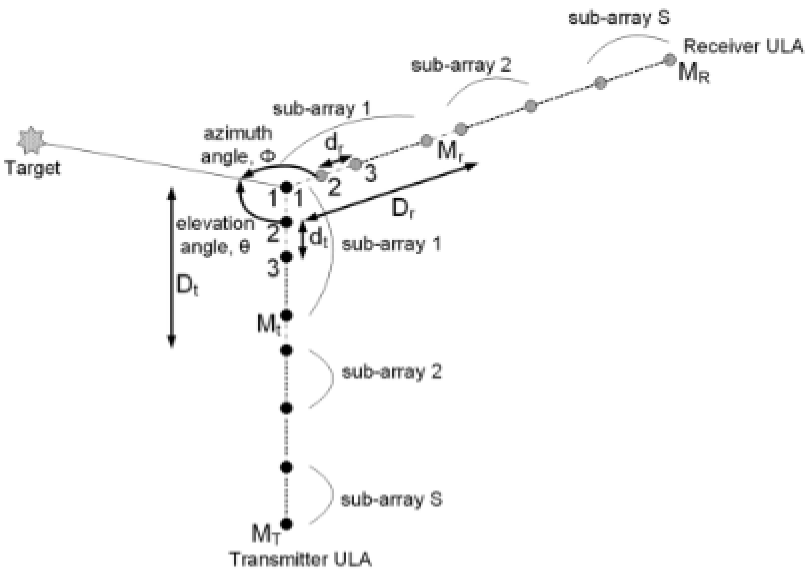

Figure 3.2: Mills Cross in Sonar

operating frequency, d_t is inter element distance in the sub array, M_t is the number of elements in the sub array and c is the speed of the sound.

$$\bar{w} = [1\ e^{-j(2\pi f d_t \cos\theta_0/c)} .... e^{-j(M_t-1)(2\pi f d_t \cos\theta_0/c)}]^T \tag{3.1}$$

The signal transmitted from the $i_t h$ sub array at an elevation angle θ_0 and target at θ_t is given by equation 3.2. if both elevation angle θ_0 and target angle θ_t are same then we may get gain of M_t.

$$s_{\theta,i}(t) = \bar{a}_t^T(\theta_t)\bar{a}_t^*(\theta_0)s_i(t) \tag{3.2}$$

Now with conditions from now on consider each sub array as single element, transmit steering vector $\bar{a}_T(\theta_t)$ can be written as equation 3.3. Here D_t is the distance between phase centers of sub arrays.

$$\bar{a}_T(\theta_t) = [1\ e^{-j(2\pi f D_t \cos\theta_t/c)} .... e^{-j(S-1)(2\pi f D_t \cos\theta_t/c)}]^T \tag{3.3}$$

Therefore the total signal due to all transmit sub arrays for target elevation angle as θ_t is in equation 3.4

$$s_{\theta,TOT}(t) = \bar{a}_t^T(\theta_t)\bar{s}_\theta(t) \tag{3.4}$$

$$\bar{s}_\theta(t) = [s_{\theta,1}(t).........s_{\theta,S}(t)] \tag{3.5}$$

Here $\bar{s}_\theta(t)$ is the combination of all orthogonal signals.

Similarly we can assume the same approach of sub arrays can be in case of receive arrays also. Received signal vector can be written as per equation 3.6.

$$\bar{x}_\theta(t) = \alpha\bar{a}_R(\phi_t)s_{\theta,TOT}(t) \tag{3.6}$$

Array steered to Azimuth direction ϕ_0, ϕ_t is the target direction and $\alpha\bar{a}_R(\phi_t)$ is the receive steering vector mentioned in equation 3.7.

$$\bar{a}_R(\theta_t) = [1\ e^{-j(2\pi f D_r \cos\theta_t/c)} .... e^{-j(S-1)(2\pi f D_r \cos\theta_t/c)}]^T \tag{3.7}$$

D_r distance between the phase centers.

The receive signal vector at $i^t h$ receive sub array can be written as

$$\bar{y}_i(t) = \alpha\bar{a}_r(\phi_t)a_{R,i}(\phi_t)s_{\theta,TOT}(t) \tag{3.8}$$

$a_{R,i}(\phi_t)$ is the $i^t h$ element (sub array) steering vector.

In receive all the sub arrays are forming beams in particular Azimuth direction of ϕ_0 $i^t h$ receive sub array produces the signal given in equation 3.9

$$\bar{y}_{i,\phi_0}(t) = \alpha \bar{a}_r^T(\phi_0)\bar{y}_i(t) \tag{3.9}$$

where $\alpha \bar{a}_r^T(\phi_0)$ are the coefficients of the spatial filter at an azimuth angle ϕ_0.

To get the MIMO benefits after the beam forming we need to do the matched filtering to get the each transmitted orthogonal signal. The matched filter enhances the energy, we can state that by recalling equation 3.10

$$\int_0^T s_i(t)s_j(t)dt = Es,\ if\ i = j;\ else\ 0 \tag{3.10}$$

where E_s is the energy of the signal and T is the duration of the pulse. The output sampled at the output of the matched filter can be written as per the equation 3.11

$$\bar{y}_{i,k} = \alpha a_{R,i}(\phi_t)\bar{a}_r^H(\phi_0)a_{T,k}(\theta_t)\bar{a}_t{}^T(\theta_t)\bar{a}_t{}^*(\theta_0)E_{sk} \tag{3.11}$$

By defining the complex coefficients β_r and β_t as mismatch between the exact target direction and steering direction of the receiver and transmitter. we can write the final output of the each matched filter 'k' can be written as equation 3.14.

$$\beta_r = \bar{a}_r^H(\phi_0)\bar{a}_r(\phi_t) \tag{3.12}$$

$$\beta_t = \bar{a}_r^T(\theta_t)\bar{a}_r(\theta_0) \tag{3.13}$$

$$y_{i,k} = \alpha\beta_r\beta_t E_s a_{R,i}(\phi_t)a_{T,k}(\theta_t) \tag{3.14}$$

Finally **Y** can be written in matrix form composed of all possible combinations of i,k as per the equation 3.15 which is sxs matrix, where s is the number of sub arrays in each Transmit and Receive arrays.

$$\mathbf{Y} = \alpha\beta_r\beta_t E_s\bar{a}_R(\phi_t)\bar{a}_T(\theta_t) \tag{3.15}$$

3.1.2 Mills Cross Radar

The Mills Cross architecture is composed of a uniform linear array of 30 receiver elements and a uniform linear array of 30 receiver elements which are perpendicular to each other as shown in Fig 3.3. Additionally, we assume that the overall array is looking forward to receive the information from both azimuth and elevation planes.The above signal model defined for Mills Cross sonar can be adapted to the Mills Cross Radar. The transmitters are at the end of the both linear arrays, we have used 4 different transmitters. As shown in figure 3.3 each linear array has two transmitters to radiate the orthogonal waveforms. To simplify further we need not

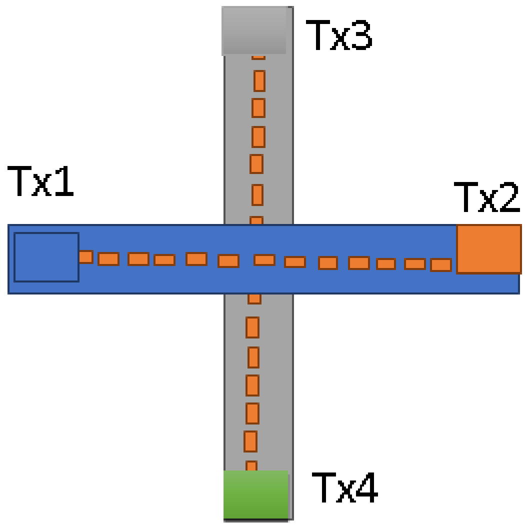

Figure 3.3: Proposed MIMO Mills Cross Radar Receive Array Architecture

define the signal model for both Horizontal and Vertical receive arrays. Simulations are also carried out for the single array which can be extended to other array. By simple data fusion we can combined the each array output at the data level.

In this configuration, the phase references of the uniform linear arrays are assumed to be the leftmost elements.

To be able to utilize MIMO radar techniques, whereas signals of different transmitters are orthogonal or uncorrelated. In the receiving mode, the outputs of the elements of a receiver arrays are spatially filtered (i.e., beam forming) and synthesized the beams to detect a possible echo at the azimuth and elevation planes [4]. Moreover, each receive element contains filters matched to the transmitted signals to obtain the MIMO radar structure. The outputs of the matched filters that filters the incoming signals with respect to all of the transmitted signals at each receiver element, can be used to estimate the parameters such as target angles in azimuth and elevation.

Here in our Linear array there is no transmit array to form the multiple beams in the transmit, it was assumed that transmit antenna illuminated the entire area, so the equation 3.5 is not a function of any angle.

Since we are assuming that all the beams are formed in the array plane and present all the time, unlike in Mills Cross Sonar it was scanned. The receive steering vector is of 24x30 as we are forming 24 beams from the 30 receive elements. We will have Receive steering vector for each beam pointing angle. The equation 3.7 is for one beam pointing direction of θ_t, like that we will have 24 steering vectors. The final equation 3.15 for one linear array will be 2x30 as we have used two transmitters and 30 receive elements.Each linear array gives 2x30 signals as output, we can process them independently and combine at data level.

3.2 Ambiguity Analysis

In traditional radar ambiguity function represents the energy spread in the range and Doppler domains, with the help of this we can identify resolution capabilities of a radar system. In MIMO radar ambiguity is function of angle also, that means our signal energy can be spread based on the angle of scan also. Detailed ambiguity analysis for the each type of MIMO waveforms carried out and their ambiguity diagrams has been studied and reported in literature [17].

We consider a transmitting array of M Antennas and a receiving array of N antennas. The position of the $m_t h$ element of the transmitting array is denoted by the vector $X_{Tx,m}$, while the position of the nth element of the receiving array is denoted by the vector $X_{Rx,n}$. Cohrent MIMO configuration was assumed, in our case M=2 and N=30.

Waveform radiated from the mth Antenna is given by the equation 3.16

$$s(t,\theta) = \sum_{m=1}^{M} g_{Tx,m}(\theta) e^{j\mathbf{X}_{Tx,m}^{T}\mathbf{k}(\theta)} s_m(t) \tag{3.16}$$

where θ is the considered direction, k(θ) the wave vector, $g_{Tx,m}(\theta)$ the gain of transmitting element m in direction θ. If we assume the transmit radiates in all direction uniform (Omni Antenna). We have considered the expression to incorporate pattern changes, as realizing the ideal omni antenna is difficult.

The received signal from a target which is in the direction θ_t.

$$s_n^r(t) = g_{Rx,n}(\theta_t) e^{j\mathbf{X}_{Rx,n}^{T}\mathbf{k}(\theta_t)} \sum_{m=1}^{M} g_{Tx,m}(\theta_t) e^{j\mathbf{X}_{Tx,m}^{T}\mathbf{k}(\theta_t)} s_m(t-\tau) e^{j2\pi v_t t} \tag{3.17}$$

τ corresponds to delay and v_t corresponds to doppler

$g_{Rx,n}(\theta)$ the gain of receive element n in direction θ.

In our case we have planned to have simultaneous beams (Ubiquitous), we will have multiple signal for each beam pointing angle.

Final Ambiguity equation for the MIMO waveform is given in equation 3.18

$$A_r(\tau, v, \theta) = \left(\sum_{n=1}^{N} e^{-j\mathbf{X}_{Rx,n}^{T}\mathbf{k}(\theta)} \times \left(\sum_{m=1}^{M} e^{-j\mathbf{X}_{Tx,m}^{T}\mathbf{k}(\theta)} \int s_n^r(t) s_m^*(t+\tau) e^{-j2\pi v t} dt \right) \right) \tag{3.18}$$

The Ambiguity equation has three components Doppler, time delay and direction unlike traditional radars where it's a function of only Doppler and time delay.

Detailed analysis of the ambiguity for different waveforms done in the literature [16] and [18].

3.3 Summary

Proposed Mills Cross MIMO sonar signal model was utilized and extended for Mills Cross MIMO Radar. Ubiquitous radar concepts have simplified the signal model further. Proposed Mills Cross MIMO Radar has multiple signals for each beam pointing direction. Proposed scheme is implemented in the Matlab and resultant pattern has been verified. These results are presented in the chapter 4. All the radar processing chain was implemented as the resolving capability of the targets with virtual array also has been demonstrated in chapter 4.

Chapter 4

Implementation and Result Analysis

Entire project objectives were divided in to the 3 parts 1. Realizing the Ubiquitous radar concept 2. Implementing the ubiquitous concepts to modified Mills cross 3. Implementing the MIMO concepts for the modified Mills cross Radar. The simulation is carried out in Matlab by using Phased Array toolbox [19].

4.1 Ubiquitous Mills Cross Radar

To prove this working of the Mills cross radar linear arrays of the required Azimuth beam widths were simulated. Synthesized the beams in Azimuth and Elevation to cover the required area. Simulated the target and processed to detect the presence of target and identified the positional information of the target.

Parameters considered for the simulation for Azimuth and Elevation Array

- Number of Rx Elements: 30
- Two arrays perpendicular to each other
- Number of Beams: 24 each in Azimuth and Elevation
- Frequency of Operation: 10GHz
- Beam width: 4.3°
- Element Spacing: $\lambda/2$

To cover the entire Azimuth and Elevation area 24 simultaneous beams were formed in both Azimuth and Elevation (Refer Figs 4.1 and 4.3). As we can see from the figures 4.2 and 4.4 we can observed that we could resolve only in one dimension. As per the combined output of the surface plot in fig 4.5, We can implement modified Mills cross architecture-based Radar Processing and get the positional information clearly. From the beam response we can identify the positional information as in fig 4.6. Here we could achieve this performance with out having rectangular array.

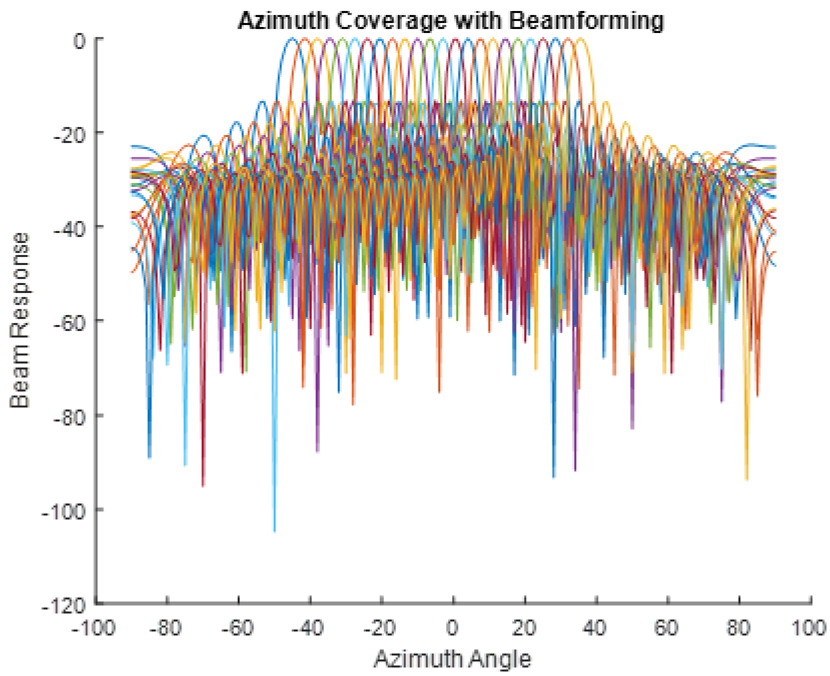

Figure 4.1: Azimuth Coverage with Beam forming

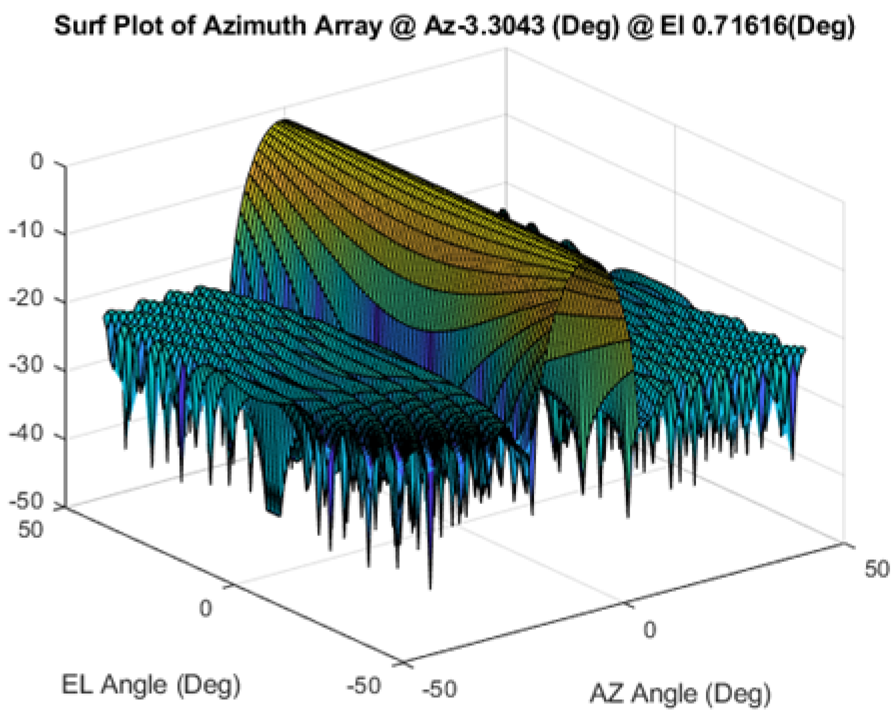

Figure 4.2: Surface plot of Azimuth Linear Array

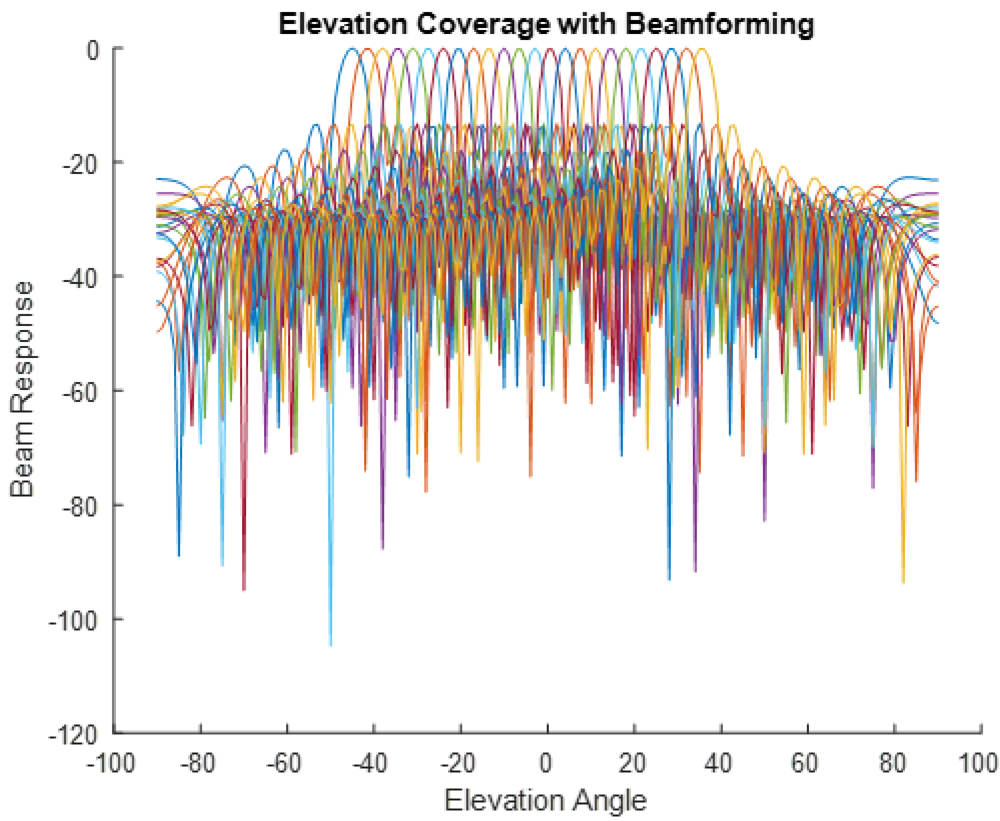

Figure 4.3: Elevation Coverage with Beam forming

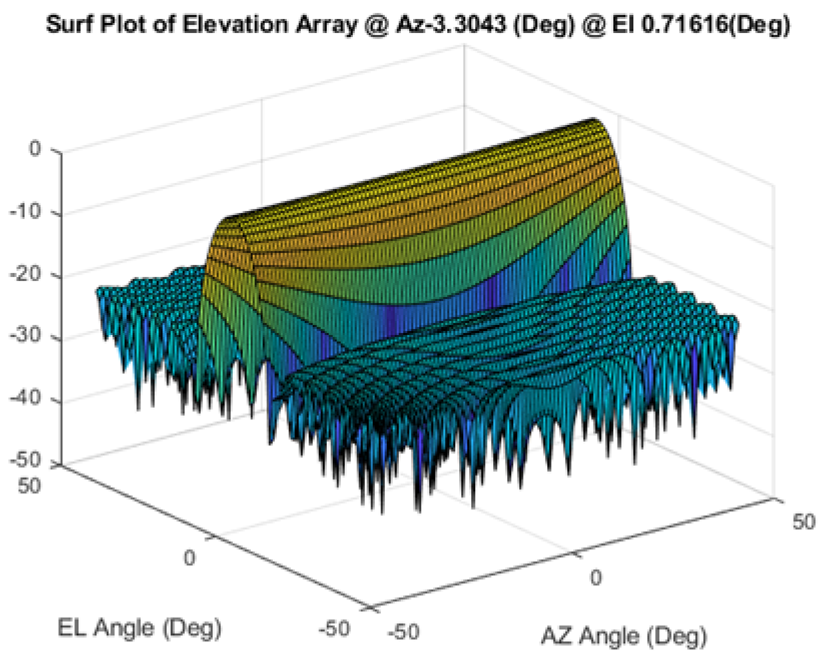

Figure 4.4: Surface plot of Elevation Linear Array

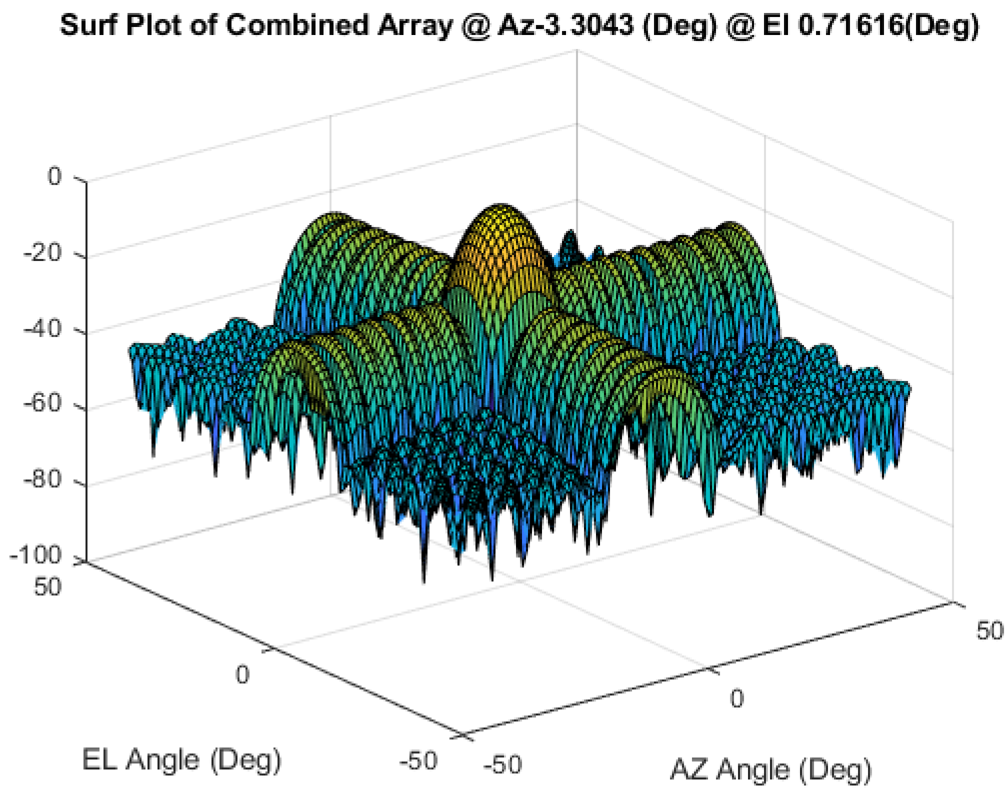

Figure 4.5: Combined Surface plot of Az and El Linear Arrays

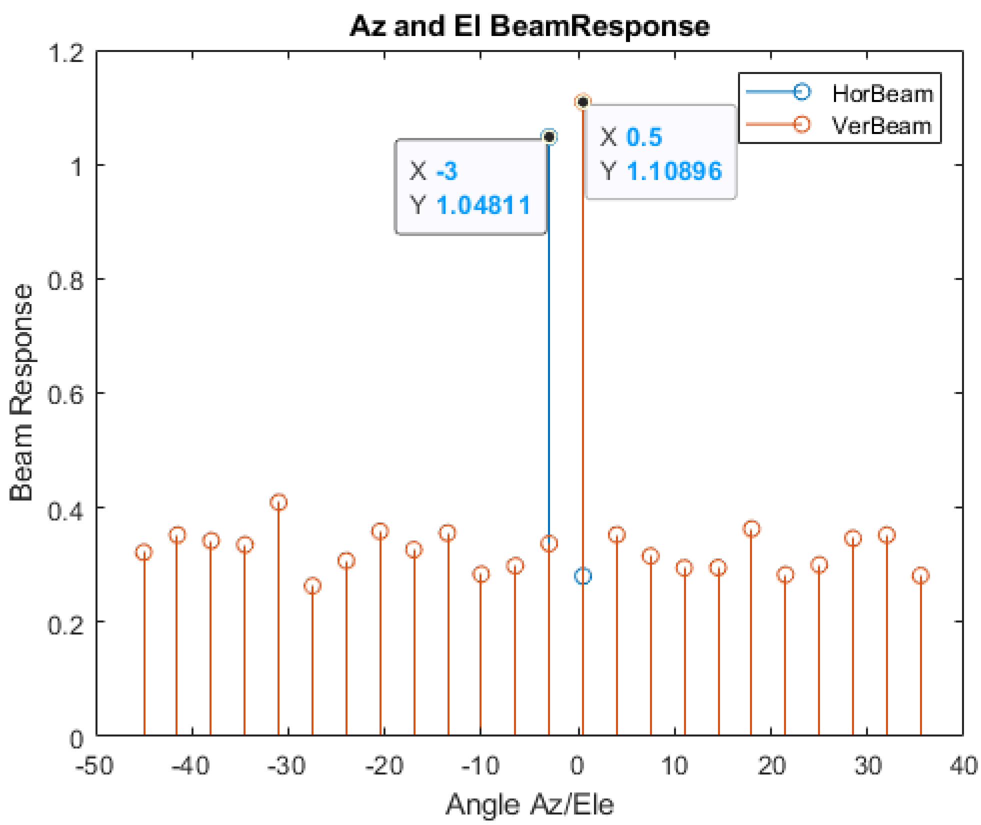

Figure 4.6: Combined Surface plot of Az and El Linear Arrays

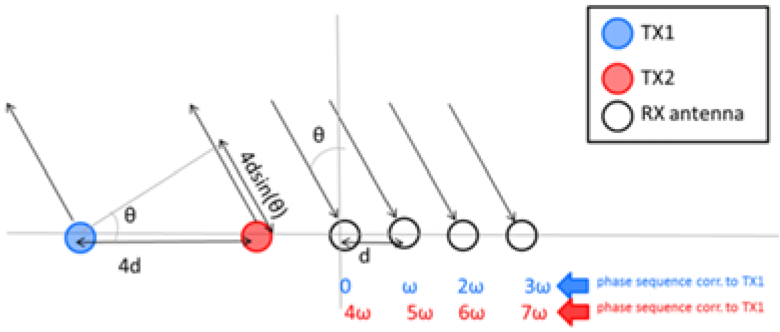

Figure 4.7: Preliminary Array to realize Virtual Array

4.2 MIMO Mills Cross Radar

4.2.1 Proto Array

To improve the angular accuracy of the modified Mills cross Radar, it was planned to use the MIMO diversity properties. The main idea is to utilize the available resources and try to improve the angular accuracy. To prove the concept initially preliminary array shown in 4.7 was implemented and verified the beam width of the virtual array. As shown in the fig 4.7, I have used 4 receive elements and try to realize a virtual array of 8 receive elements by simply adding an additional transmitter. Both transmitters radiate orthogonal waveforms and these waveforms are extracted by implementing a matched filter at each receive element. As we can observe from the results from fig 4.8 beam width of the antenna has reduced to the half.

4.2.2 Proposed Array

Main idea is to use the available 30 receive elements as shown in fig 4.9 and try to realize the virtual array of the length of 60 receive elements. Each transmitter excitation is recovered and used to obtain the virtual array.

From the figs we can say that the we could achieve virtual array. As the virtual array beam width is less compared to physical array, we tend to have nulls in the coverage. So, when we switch to virtual array beamforming coefficients has to be changed as per the new beam pointing. So virtual array configuration can be used only in the tracking mode as the coverage has come down to half.

From the figs 4.10 and 4.12 we can observe that after realizing the virtual array in order to cover the entire area we may face some coverge holes, that means we may get some blind areas in Azimuth and Elevation. As the virtual array beam width is less compared to physical array, we tend to have nulls in the coverage. So, when

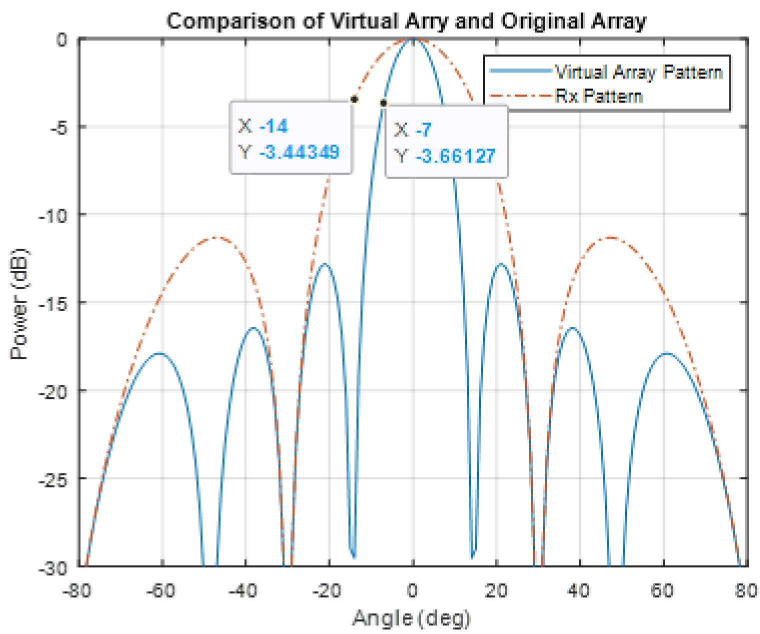

Figure 4.8: Realize Virtual Array Beam width comparison with Physical Array

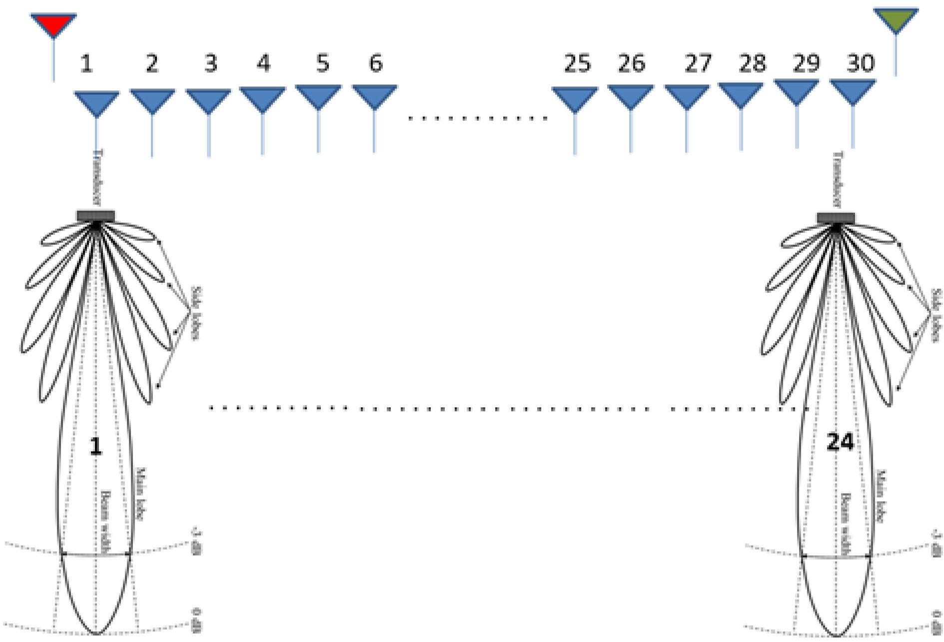

Figure 4.9: Proposed Linear Array

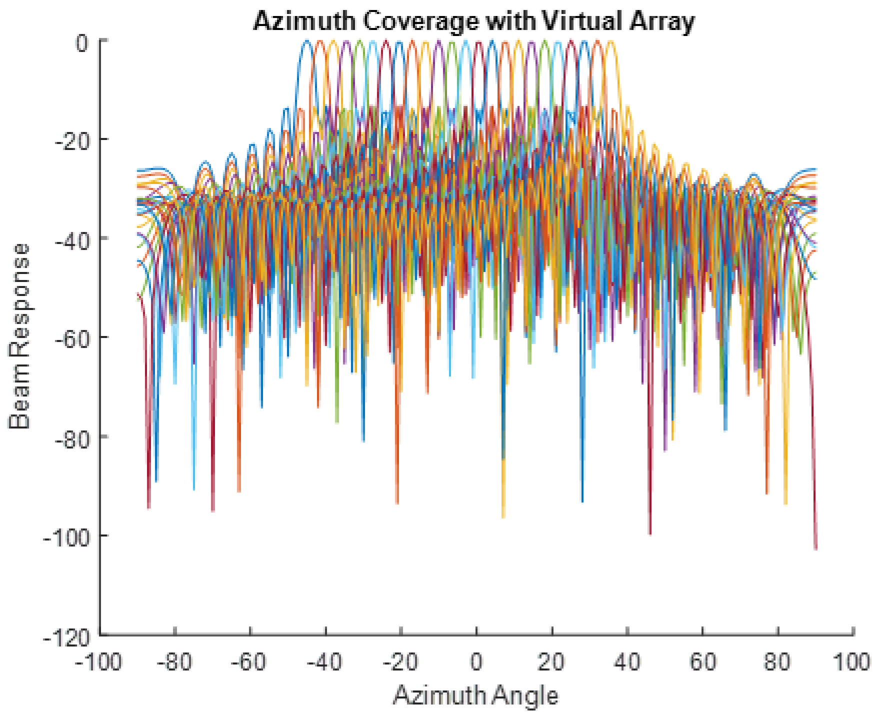

Figure 4.10: Coverage with Narrow beam with covering entire Azimuth

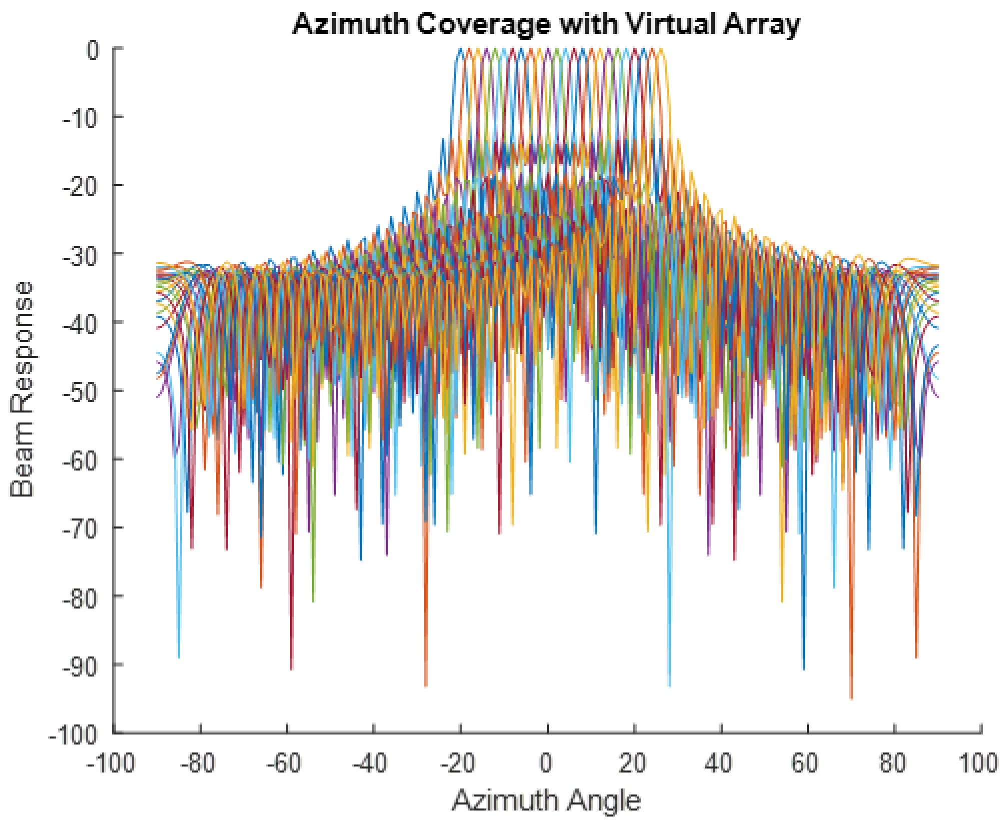

Figure 4.11: Coverage with Narrow beam with covering part of the Area in Azimuth

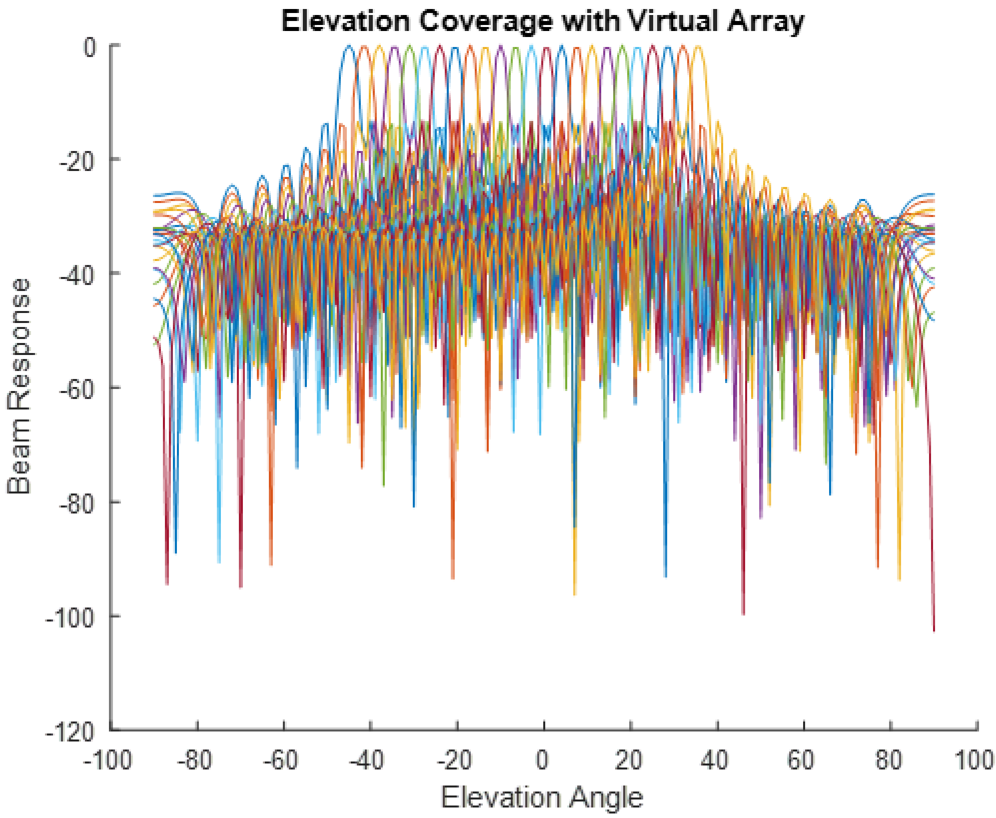

Figure 4.12: Coverage with Narrow beam with covering entire Elevation

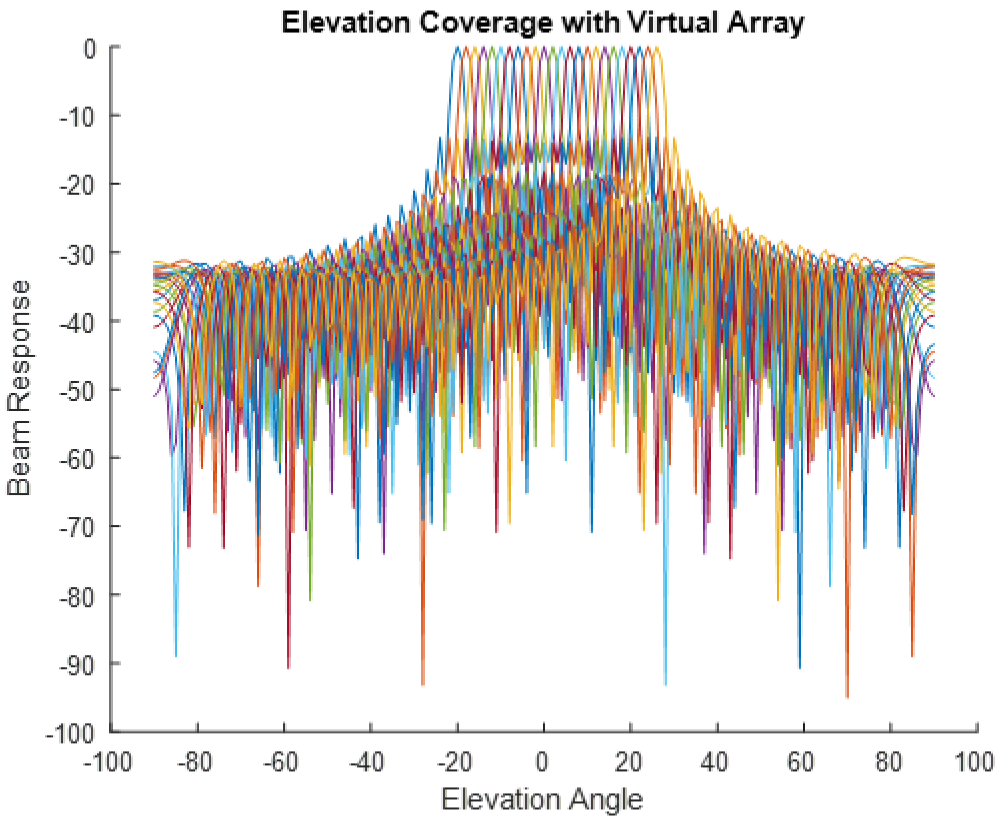

Figure 4.13: Coverage with Narrow beam with covering part of the Area in Elevation

we switch to virtual array beam forming coefficients has to be changed as per the new beam pointing. So virtual array configuration can be used only in the tracking mode as the coverage has come down to half. In the tracking mode we need not to scan entire area and coverage has come down as shown in figs 4.11 and 4.13.

4.2.3 Signal Processing to resolve the Targets in Angular space

In order to prove the target resolving capability with the virtual array, radar signal processing chain has been implemented. Implemented Signal processing chain has been used with both physical and virtual array and results were summarized below.

Table 4.1: Attributes Considered in Simulation

Target Range	40cm and 50cm
Target Speed	-20m/s and 28m/s
Target RCS	$20m^2 and 40m^2$
Target model	Swerling Type 2
Antenna	Vitual Array
Orthogonal Waveform	Time division and up and down chirps
Signal Processing Chain	FMCW
Waveform	LFM

The resolving capability was checked by implementing the direction of arrival algorithm [20]. As we can see from the figs 4.14 and 4.15 virtual array could resolve up to 2 degrees separated targets. We can implement similar kind of approach for the orthogonal array to resolve the targets in the other dimension.

4.2.4 Range Doppler Processing

From fig 4.16 we can say that by using the MIMO Mills cross radar we can extract the target information with better angular accuracy. The array performance is satisfactory and we could resolve the targets in Range and Doppler domain also.

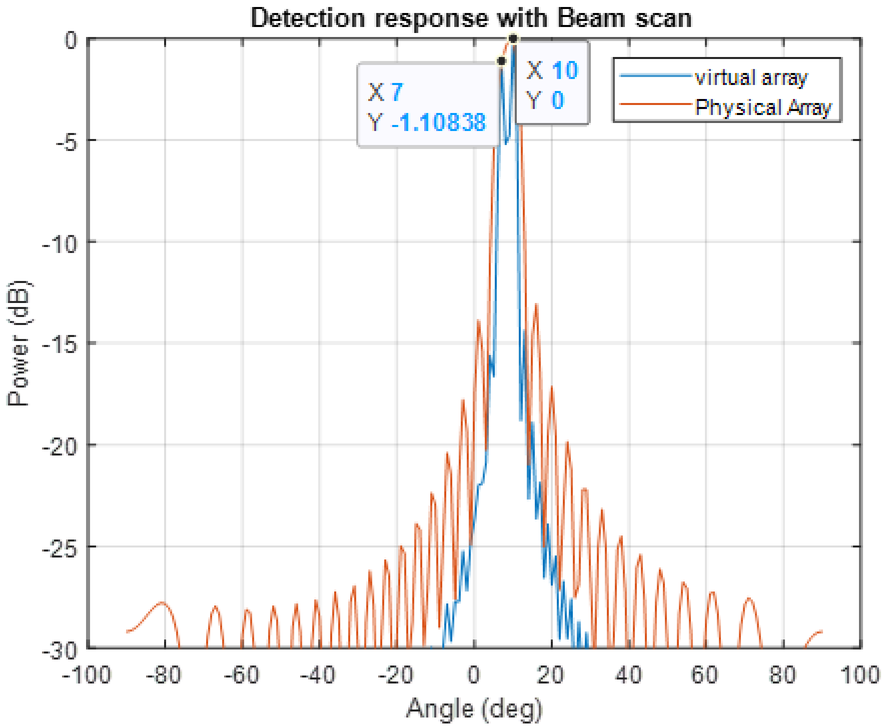

Figure 4.14: Comparison resolving capability of Virtual Array and Physical Array

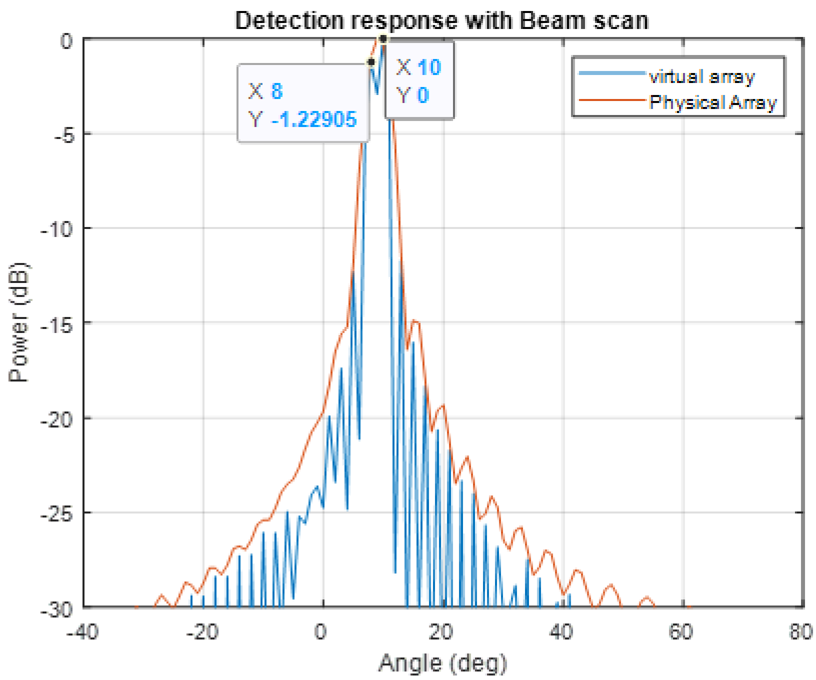

Figure 4.15: Comparison resolving capability of Virtual Array and Physical Array

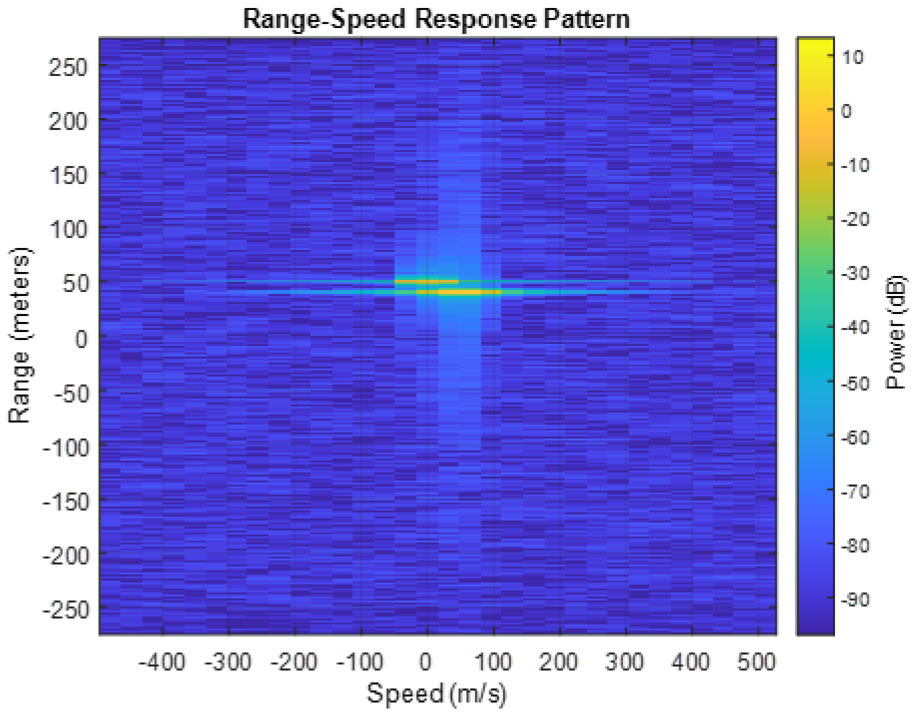

Figure 4.16: Range Doppler Response for FMCW waveform

Chapter 5

Conclusion and Future Work

Architecture and signal processing schemes proposed are the best solution to scan large volume of area in small time. Additional MIMO architecture has provided flexibility in improving the positional accuracy with the available resources. It has another additional advantage like Low Probability of Intercept, less clutter reflections as transmitted power is very less compared to traditional radars. Better configurability can be achieved as switching from the surveillance to tracking can be done by software.

In future we can try to explore the possibility of the sparse arrays with MIMO to reduce further the receive elements requirement. In certain cases, we can reverse the role of the transmitter and receiver arrays to achieve the similar performance to reduce the ADC requirement. For long range applications better codes can be designed with optimization concepts by defining proper cost function[21].

In this solution it was assumed that transmitters can illuminate the entire area. Receive chain design has to be done carefully to avoid the transmitter leakage in the FMCW configuration.

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