Cloud Publications
International Journal of Advanced Electronics and Radar Technology
2014, Volume 2, Issue 1, pp. 11-20, Article ID Tech-252

Review Article | Open Access

Application of Phased MIMO Radar Technology for AWACS System

Vidya Sawant

Department of Electronics and Telecommunication, Mukesh Patel School of Technology, Management and Engineering, NMIMS University, Mumbai, Maharashtra, India

Correspondence should be addressed to Vidya Sawant, vidya.sawant@nmims.edu

Publication Date: 28 April 2014

Article Link: http://technical.cloud-journals.com/index.php/IJAERT/article/view/Tech-252

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Abstract Phased Multiple-Input Multiple-Output (PMIMO) radar is currently an active area of research. The MIMO technique well studied and developed over the years exploits the multipath environment to its benefit for providing reliable and faster communication. Incorporating the MIMO concept in radar design to provide independence between the transmitted signals with each transmit antenna transmitting orthogonal signal provide distinct advantages over the phased array system with respect to the maximum number of targets that could be uniquely identified, increased degree of freedom, higher angular resolution, better parameter identifiability and RCS estimation. However the system lacked the coherent processing gain feature that allowed beam steering in phased array radar. MIMO technique applied to the traditional Phased array radar was investigated and was found to offers numerous advantages over both the phased array radar system and the MIMO radar. The goal of this paper is to elucidate the key concepts of the MIMO radar and PMIMO radar technology that can be incorporated in an Airborne Warning and Control System as an improved and alternative radar arrangement.
Keywords *Phased MIMO Radar; Beamforming; Coherent Processing Gain; Collocated Antennas*

1. Introduction

Airborne Warning and Control System known as the AWACS system involves radar system on the aircraft for surveillance of hostile targets, control of weapons to guide missiles and fighter aircrafts. The traditional radar systems used are the phased array radars which consists of array of transmit and receive antennas in a fixed configuration. There are various antenna array configurations used by AWACS system, one of them being the use of one or more conformal antenna array which is affixed on the exterior of the fuselage of the aircraft. This antenna array is mounted above and below the body (fuselage) of the aircraft in a plane parallel to the longitudinal axis of the aircraft. The traditional signal processing used by this system involves transmitting the same waveform by the individual elements of the transmit array to cohere the beam to focus the energy in the desired direction as well as to steer it electronically for target tracking. This kind of a system though capable of focusing and steering the transmit energy, offers low probability of target detection due to target fading which affects the received SNR.

The requirement of many emerging applications has led to the advancement in the antenna array and processing technologies. One such advancement is the use of Multiple-Input Multiple-Output technology for radar systems. The key ideas of MIMO radar concept has been picked up from MIMO communications. MIMO is a technique used in communications to increase data throughput and link range without additional bandwidth or transmit power. This is achieved by higher spectral efficiency and link reliability or diversity [2]. Using MIMO systems in communications made significant improvements when there is serious fading in the communication channel. Radar systems also suffer from fading when there are complex and extended targets. Researchers took the idea of using multiple transmit and receive antennas to overcome the effects of fading from communications and applied it in the field of radar to achieve performance improvements [2].

Although MIMO radar systems resemble phased array systems, the fundamental difference between them is that MIMO radar always transmits multiple probing signals, via its transmit antennas, which may be correlated or uncorrelated with each other, whereas phased array radars transmits scaled versions of a single waveform which are fully correlated. There are two basic regimes of MIMO radar considered in the literature. The multiple transmit and receive antennas of a MIMO radar system may be widely separated as radar networks providing independent scattering responses to each antenna pair referred to as distributed MIMO radar system [20]. Whereas the second regime, which has the transmit and receive antenna elements closely spaced so that the target is in far field modelled as point source is called as collocated MIMO radar system [4]. The fundamental difference between the two is that in distributed MIMO radar independent radars that form the network perform a significant amount of local processing and there exists a central processing unit that fuses the outcomes of central processing in a reasonable way. For example, every radar makes detection decisions locally then the central processing unit fuses the local detection decisions. Whereas, in collocated MIMO radar uses all of the available data and jointly processes signals received at multiple receivers to make a single decision about the existence of the target. MIMO radar with widely separated antennas has the advantage of viewing the target from several distinct aspect angles. The radar cross section (RCS) of the target varies with the aspect angle and thus widely separated MIMO radar system can exploit spatial diversity effectively [21]. Whereas MIMO radar with collocated antenna offers an improved DOA estimation performance, higher resolution, higher sensitivity by forming a virtual array with a larger number of virtual antenna elements as compared to the traditional phased array radar [4]. Due to the restricted area for placing the transmitter and receiver antennas with a conformal design on the fuselage, collocated MIMO radar has been suggested as suitable choice for AWACS system. This model however lacked the coherent processing gain provided by a phased array radar system and depicted a poor interference rejection performance [7]. Attempts were made to jointly exploit the advantages of processing gain of phased array and waveform diversity for MIMO systems which was reported by the work carried by Hassanien *et al* [5]. The authors proposed MIMO phased array radar, a trade off between the phased array and the traditional MIMO radar was achieved which gives best of both configurations, i.e., the increased number of virtual antenna elements due to use of waveform diversity together with SNR gain due to sub aperture based coherent transmission. The proposed method [5] is based in portioning the transmit array into a number of uniform overlapping sub arrays with each sub array transmitting orthogonal waveforms at same carrier frequency. The new radar technology proposed [5] enjoyed all the advantages of the MIMO radar [3] i.e. improved parameter identifiability, extending the array aperture detecting higher number of targets, enables the use of existing beam forming techniques at both the transmitting and the receiving ends, provides a means of designing the overall beam pattern of the virtual array and offers improved robustness against strong interference.

2. Collocated MIMO Radar Signal Model

Consider a radar system having N_t number of transmit and N_r number of receive antenna elements in the transmit and receive array. The system transmits N_t orthogonal waveforms $x\ (t) = [x_1(t),\ x_2(t),.....,\ x_{Nt}(t)]^T$ from the N_t transmit antennas which satisfies the orthogonaility condition.

$$\int_{To} x\ (t).\, x^H(t)d(t) = I_{Nt} \tag{1}$$

Where, T_o is the radar pulse width, t is the time index within the radar pulse, I_{Nt} is the N_t x N_t identity matrix, and $(\cdot)^T$ and $(\cdot)^H$ stand for the transpose and Hermitian transpose, respectively.

The target is assumed to be in the far field of transmit and receive array with θ_t as the target direction from the transmit array and θ_r being the target direction from the receive array. The transmit and receive array antenna elements are assumed to be located close to eachother so that they view the target as a point target in the same direction. Under this assumption of co-located transmit and receive antennas in the array it is reasonably assumed that θ_t=θ_r=θ. Since the waveforms generated by each element in the transmit array travels a different path length towards the target with a target location of θ. The signal that arrives at the target is given by

$$x_{tar}(t) = a^T(\theta)x(t) \tag{2}$$

Where, $a(\theta)$ is the transmit steering vector used to model the effect of different path lengths from each transmit array to the target at location θ given as

$$a^T\ (\theta) = \left[\, e^{-j2\pi f o \tau_{N1}(\theta)} e^{-j2\pi f o \tau_{N2}(\theta)} \ldots \ldots .. e^{-j2\pi f o \tau_{Nt}(\theta)} \right] \tag{3}$$

Where, f_o is the carrier frequency of the radar and τ_{Nt} is the time taken by the signal emitted by the n^{th} tranmit antenna to the target.

This signal $x_{tar}(t)$ arriving at the target is reflected and received by the elements of the receive array along with the interference, jamming and noise components respectively. Under point target assumptions the signal reflected from the target and received by the receiver array can be written as

$$y(t) = x_{tar}(t) + z(t\ ) \tag{4}$$

Substituting $x_{tar}(t)$ from equation (2) the received signal can be written as

$$y(t) = [a^T(\theta)x(t)]\beta(\theta)b(\theta) + z(t) \tag{5}$$

where, $\beta(\theta)$ is the complex reflection coefficient proportional to the radar cross section of the reflecting target and depends on the orientation of the target, $z(t)$ represents the interference, jamming and noise that will be received by the receiver in addition to the signal reflected by the target, $b(\theta)$ is the receiveing steering vector associated with the direction θ.

When a set of orthogonal MIMO signals is transmitted, the transmitter pattern is omnidirectional. However, on reception the returns due to the n^{th} transmitted waveform can be recovered by matched filtering the received signal with each of the waveform $\{x_n(t)\}_{n=1}^{Nt}$ to separate the received signal into N_t transmitted signals. The matched filtering operation can be given as

$$s_n\ (t) = \int_{To} y(t)x_n^*\ (t)dt, \qquad n = N_1, N_2\, , \ldots . N_t \tag{6}$$

Substituting the expression for the received signal from equation (5)

$$s_n\ (t) = \int_{To} a(\theta)x_n\ (t)\beta(\theta)x_n^*\ (t)dt + z(t)x_n^*\ (t), \qquad n = N_1, N_2\, , \ldots . N_t \tag{7}$$

Solving the above equation by applying the orthogonality condition of $x(t)$ we get

$$s_n(t) = \beta(\theta)a(\theta) \otimes b(\theta) + \hat{z}(t) \quad (8)$$

Where, $\otimes$ is the Kronecker product and ẑ(t) is the white noise which has guassian distribution.

Therefore by applying matched filtering operation, the target information can be extracted. A receive beampattern can then be formed by applying a weight coefficient to each of the filtered output which maximizes the received energy enabling better parameter estimation.

3. Collocated Phased - MIMO Radar Signal Model

Consider a radar system having N_t number of transmit and N_r number of receive antenna elements in the transmit and receive array which are located close to each other in space so that they view the target in the far field as a point source model. In phased MIMO radar, the transmitting array of N_t antennas is partitioned into P overlapped subarrays where $1 \leq P \leq N_t$. The p^{th} sub array includes the antenna located at the p^{th} upto the $(N_t - P - p)$ position forming an overlapped subarray [6]. The signal waveform applied to each of the element of the p^{th} subarray is weighted appropriately by a beam forming coefficient in order to coherently transmits the signal $x_p(t)$ so that the beam formed by the array is focused towards the target direction. At the same time, the waveform transmitted by each sub array is uncorrelated with the waveform transmitted by the other arrays. This allows for P orthogonal and focused beams are transmitted to scan the target area.

The signal transmitted by the antennas of the p^{th} subarray is modelled as:

$$s_p(t) = \sqrt{\frac{N_t}{P}}\, x_p(t) w_p^* \quad , \qquad p = 1, \ldots.., P \quad (9)$$

where, w_p is the unit norm complex vector associated with the p^{th} subarray, $x_p(t)$ are the orthogonal waveforms, $(\cdot)^*$ denotes the conjugate operator.

The reflected signal from the target located in the far field at a direction of θ with respect to the radar can be modelled as

$$r(t,\theta) = \sqrt{\frac{N_t}{P}}\, \beta(\theta)(c(\theta) \odot d(\theta))^T x_P(t) \quad (10)$$

where, $\beta(\theta)$ is the target refection coefficient of the hypothetical target, $c(\theta)$ is the Px1 transmit coherent processing vector.

$$c(\theta) \triangleq [w_1^H a_1(\theta), \ldots\ldots, w_P^H a_P(\theta)]^T \quad (11)$$

Where, $a_p(\theta)$ is steering vector of the p^{th} subarray, $d(\theta) \triangleq [e^{-j\tau_{N_1}(\theta)}, \ldots.. e^{-j\tau_{N_t}(\theta)}]^T$ is the p x1 waveform diversity vector. $\tau_p(\theta)$ is the time required for the wave to travel from the first element of the first subarray to the first element of the p^{th} subarray. $x_P(t) = [x_1(t), \ldots.., x_P(t)]$ is the P x1 vector of waveform and $\odot$and $(\cdot)^T$ standing for Hadamard product and transpose, respectively. The N_rx1 received complex vector is

$$y(t) = r(t,\theta_t)b(\theta_t) + \sum_{i=1}^{I} r(t,\theta_i)\, b(\theta_i) + n(t) \quad (12)$$

where, I is the number of interferences $r(t,\theta_i)$ $(i = 1, \ldots, I)$ are the interference signals reflected from the I^{th} interference located at direction θ_i ($i=1, \ldots, I$), $b(\theta)$ is the N_r x1 receiving vector and $n(t)$ is the noise term. The received echoes $y(t)$ due to the p^{th} transmitted waveform are then match filtered to each of the transmitted waveform $\{x_p(t)\}_{p=1}^{P}$, to form the PN_rx1 virtual data vector,

$$z \triangleq [\,y_1^T, \dots, y_P^T] \tag{13}$$

$$= \sqrt{\frac{N_t}{P}}\beta_t\, v(\theta_t) + \sum_{i=1}^{I}\sqrt{\frac{N_t}{P}}\beta_i\, v(\theta_i) + n \tag{14}$$

where, $\beta_t=\beta(\theta_t)$ and $\beta_i=\beta(\theta_i)$, $(i=1,2,..,I)$ are the reflection coefficients of the target and the interferences, respectively, $v(\theta_t) \triangleq (c(\theta).d(\theta) \otimes b(\theta)$ is the kN_r x1 virtual steering vector associated with direction θ, n is the PN_rx1 noise and $\otimes$ is the Kronecker product.

4. Related Research in MIMO and Phased MIMO Radar

Phased-array antennas have been widely used in different radars systems which use an electronic beam steering at the transmitter end and the receiving end of the system operating at the same frequency. The steering of the beam in the desired direction is obtained by controlling the phase shifts across the antenna elements which offers a directional gain useful in detecting and tracking weak targets as well as suppressing side lobe interferences from other directions. Multiple antennas or a multi beam antenna are required in a phased array radar system to focus the antenna beams in different directions [1]. The requirement of many emerging applications has led to the advancement in the antenna array technologies. One such advancement is the use of Multiple Input Multiple Output technology for radar systems. The development of MIMO technology played a significant role in MIMO radar and thus it is important to consider the theoretical predecessor when observing the current research area. This section presents an overview of some of the important contributions in the field.

Foschini *et al* [11] employed multiple closely spaced transmitting and receiving antennas (with typically half wavelength spacing) to increase the data rate and provide multiple paths to mitigate the fading in the channel. The capacity improvement shown by such systems was the driving factor towards the developments in MIMO technology and thus a significant amount of research was done in this area. MIMO technology exploited the multipath fading environment to provide enhancement in the communication process.

Fishler *et al* [2] was one of the first to introduce the concept of MIMO radar in true sense by exploiting the use of MIMO technology into the existing system to improve the performance of the existing phased array radar system. In this paper, the authors adopted a system that consisted of a transmit array with widely-spaced elements such that each element of the array views a different aspect of the target. The array at the receiver is a conventional array used for direction finding (DF). Fishler *et al* in his their work showed that MIMO radar leads to significant performance improvement in DF accuracy. The orthogonality of the transmitted signals provides a number of benefits for the MIMO radars, such as the diversity in the paths, virtual aperture extension, beam pattern improvement, and higher probability of detection, over the phased-array systems. The novelty of MIMO radar is that it exploits the target scintillations to improve the radar's performance. Therefore, improvements in radar performance were produced as a result of the diversity inherent in MIMO radar.

Hassanien *et al* [6] proposed a system intermediates between the two systems which jointly exploit the benefits of both the phased-array and MIMO array called as the phased array MIMO radar system. MIMO radar proposed by Fishler *et al* although showed improvements over conventional phased-arrays lacked the directional gain compared to that of phased array radar system. Therefore Hassanien *et al*, attempted to jointly exploit the benefits of MIMO radar (such as waveform diversity) with the advantages of phased array radar (such as coherent processing gain). The essence of the proposed technique is to partition the transmit array into a number of subarrays that are allowed to overlap where each subarray coherently transmits a distinct waveform which is orthogonal to the waveforms transmitted by other subarrays.

Coherent processing gain can be achieved by designing a weight vector for each subarray to form a directional beam steered towards a certain direction in space by adjusting its phase angle. Moreover, the subarrays are combined jointly to form MIMO radar resulting in higher angular resolution capabilities. Substantial improvements offered by the proposed phased-MIMO radar technique as compared to the phased array and MIMO radar techniques were reported analytically and by simulations through analyzing the corresponding beampatterns and the achievable output signal-to-noise-plus-interference ratios. The new radar technology proposed [6] enjoyed all the advantages of the MIMO radar [2] i.e. improved parameter identifiability, extending the array aperture detecting higher number of targets, enables the use of existing beamforming techniques at both the transmitting and the receiving ends, provides a means of designing the overall beampattern of the virtual array and offers improved robustness against strong interference.

Ahmed *et al* [13] suggested an alternative model of the MIMO radar developed by Fishler *et al* [2] in order to reduce the computational complexity with a relatively low side-lobe-levels in the receive beam pattern. In his proposed algorithm, the received signal vector of MIMO-radar was divided into sub-vectors, and each sub-vector was multiplied with the corresponding weight vector. The number of sub-vectors and weight vectors were optimally found to maximise the received signal power from the target of interest direction. The proposed scheme can be effectively applied in passive radars to minimise the side-lobe levels and place deep nulls for interferers in the receive beam pattern. Simulation results showed that the proposed scheme had relatively lowers side lobe levels and better detection capabilities compared to MIMO-radar and phased-array.

Wang *et al* [8] suggested frequency diversity approach to the work proposed by Hassanien [6] for further improvements in the system performance. This approach divides the transmit antenna array into multiple subarrays that are allowed to overlap, each array coherently transmits a distinct waveform, which is orthogonal to the waveform transmitted by the other subarray, at a distinct transmit frequency. A small frequency increment is employed in each subarray. Each subarray forms a directional beam and all beams are steered to different directions. The subarays jointly offers flexible modes such as MIMO array which offers spatial diversity gain, phased-array which offers coherent directional gain and frequency diverse array which provides range dependent beam pattern.

Chen *et al* [12] considered the problem of optimal MIMO radar system design using maximum channel capacity under uniform transmitted power constraint and channel constraint as the criterion for parameter estimation. He suggested that given the number of transmit and receive antennas and SNR, then the maximum channel capacity can be determined and obtained from a unique appropriate power allocation and antenna placement strategy.

5. Beamforming Methods in a Phased MIMO Radar System

Beamforming is a signal processing technique applied to transmit and receive waveforms in order to provide a directional signal transmission and reception. It involves the use of weighting coefficient applied to transmit and the receive signal which changes the amplitude and the phase of the signals at each array element and then adding them together to get the desired output. Phased array multiple-input multiple-output Radar system having its N_t transmit antenna elements partitioned into P subarrays, the uplink beamforming considers the design of weighting vectors $\{w_p\}_1^P$ for the different subarrays in order to achieve the desired beampattern in a desired direction by satisfying the transmit power requirements. Beamforming techniques can be non-adaptive transmit/receive beamformers called conventional beamformers which use a fixed set of weights and time delays for phasing to combine the signals transmitted or received by the antenna elements. Under conditions of no interferences, this beamformer provides maximum SNR, but it is not effective in the presence of directional intentional or unintentional interferences. Adaptive beamformer based on the basic concept of enhancing the signal in a particular direction while attenuating the interference and noise is able to automatically adapt its response to different situations.

A. Non Adaptive Beamforming

The conventional beamformer maximizes the highest possible output SNR gain. The signal to noise ratio of the PMIMO radar is proportional to the quantity $|w^H a(\theta_t)| \leq ||w|| \cdot ||a(\theta_t)||$, where equality holds when $w = a(\theta_t)$, which is referred to as conventional beamformer. Therefore the conventional beamformer on the transmit side have weight vector given as

$$w_p = \frac{a_k(\theta_t)}{||a_k(\theta_t)||}, \quad p = 1, \dots, P \tag{15}$$

At the receiver array, the conventional beamformer is applied to the virtual array and therefore the PN_r x1 receive beamformer weight vector is given by

$$w_d \triangleq v(\theta_t) \triangleq \left(c(\theta_t).d(\theta_t)\right) \otimes b(\theta_t) \tag{16}$$

B. Adaptive Beamforming

The receive side uses an adaptive beamformer to give an effective performance in the presence of interference. The beamforming method known as Minimum Variance Distortionless Response (MVDR) aims to minimize the interference–plus–noise power while maintaining a distortionless response towards the direction of the target. Steering the array, MVDR beamformer adaptively calculates the array weights that provide maximum gain in all directions of interest while minimizing the power in the direction of interference. The MVDR beamformer is optimization is expressed the following problem:

$$\min_{w_r} w_r^H R_{i+n} w_r, \qquad s.t.\, w_r^H v(\theta_t) = 1 \tag{17}$$

Where, w_r is the PN_r x1 receive beamforming weight vector.

The solution of (17) is given by [14] as

$$w_r = \frac{R_{i+n}^{-1} v(\theta_t)}{v^H(\theta_t) R_{i+n}^{-1} v(\theta_t)} \tag{18}$$

The practical applications of the MVDR beamforming requires online calculation of the weights according to the equation (18), that is the covariance matrix R_{i+n} should be estimated and inverted online. In practice R_{i+n} is unavailable and, therefore the sample covariance matrix $\hat{R} \triangleq \sum_{n=1}^{N_r} y_n\, y_n^H$ is used, where $\{y_n\}_{n=1}^{N_r}$ are the data snapshots which can be collected from N_r different radar pulses within a coherent processing interval.

6. Radar Detection Range Equation

This section compares the radar range equation of phased array and PMIMO radar systems; the maximum detection range satisfies [15]. The radar range equation for a phased array system transmitting an average power of P_{av} is given as

$$R_{phase} = \left(\frac{P_{av} A_r t_s \sigma}{(4\pi)^2 \boldsymbol{\kappa}\, T_s L_s\, (S/N)_{min}}\right)^{1/4} \tag{19}$$

where, P_{av} is the average transmitter power, A_r is the effective aperture of receiving antenna, σ is the radar cross section of the target, κ is the Boltzmann constant, T_s is the thermal temperature, L_s is the total loss and $(S/N)_{min}$ is the minimum detectable SNR.

The radar range equation of a PMIMO radar system considers only the p elements of the N_tN_r virtual elements which are utilized cohere a beam thereby making the effective aperture area of this system as $A_r \frac{p}{N_t\ N_r}$. The detection range of this system satisfies the following equation.

$$R_{PMIMO} = \left(\frac{P_{av} p A_r t_s \sigma}{(4\pi)^2 \kappa\, T_s L_s\, N_t N_r (S/N)_{min}}\right)^{1/4} \qquad (20)$$

7. Simulation Results

In this section, the results of computer simulation which demonstrate the comparative performance of the three systems with conventional beamforming applied to the uplink beamformer and MVDR to the downlink beamformer in order to separate out the incoming signals arrived from different azimuth directions is presented. Consider ten transmit antennas and ten receive antennas spaced half wavelength apart from each other. The normalized transmitted power as well as the overall transmit and receive power of the system is calculated and plotted by varying the azimuth in the range of -90^o to +90^o, assuming the target of interest to be located at an azimuth angle of 20^o. Transmit beampattern shown in Figure 1 shows the superior beamforming capability of the Phased array radar system due to the coherent processing gain feature offered by the larger aperture size of the phased array radar as compared to the subaperture size of 'p' of the PMIMO system. The flat transmit beampattern response of MIMO radar beampattern shown in Figure 2 depicts the lack of coherent processing gain of the system. The overall transmit and receive beampattern plot for comparing the three systems is shown in Figure 2. The main lobe of all the three radar systems in centers at the target location angle of 20^o with PMIMO radar having waveform diversity which provides lower side lobe levels compared to the other two systems.

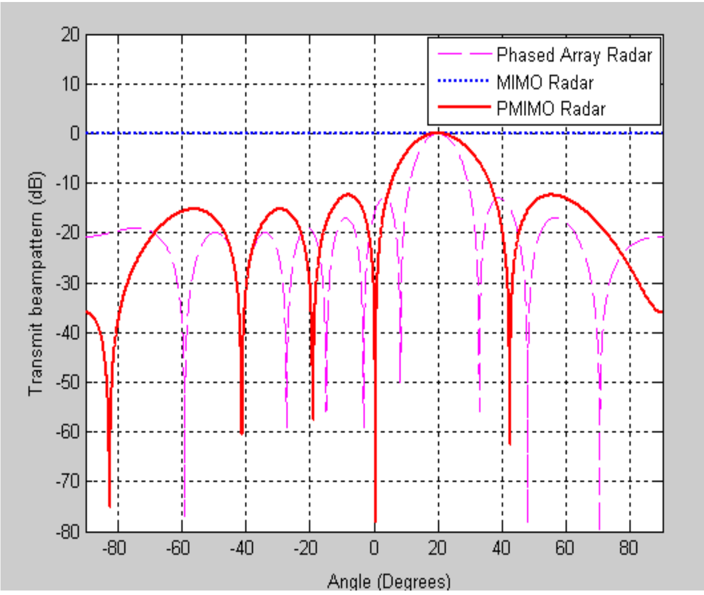

Figure 1: *Transmit Beampattern of Phased Array Radar, MIMO Radar and PMIMO Radar*

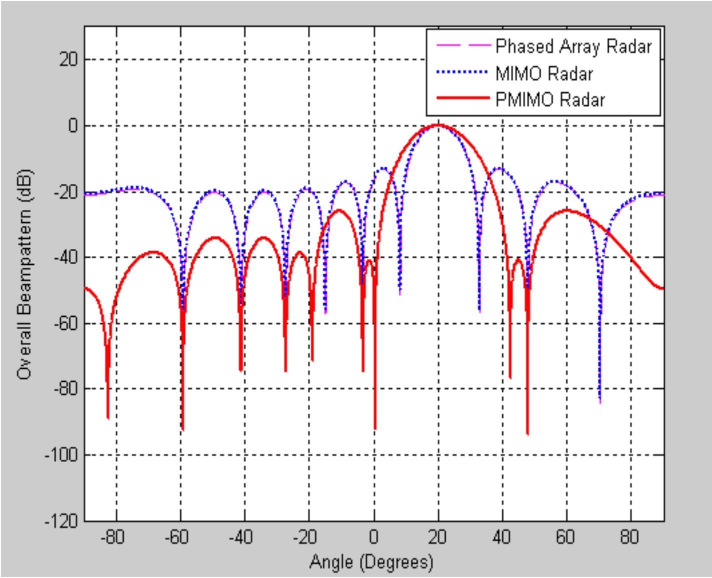

Figure 2: *Overall Transmit and Receive Beampattern of Phased Array Radar, MIMO Radar and PMIMO Radar*

8. Conclusion

Phased MIMO radar is a relatively new concept with a wide potential of applications. This paper presents the key concepts of the MIMO radar and PMIMO radar models that can be incorporated in ACWAS radar system. MIMO communication has proved to be a superior and cost effective alternative to the conventional communication system and the same can be expected from the PMIMO radar system. The potential benefits from the designed system depends on the shape, aerodynamic requirements of the aircraft, the placement of the antenna, separation between the antennas and hence expected to create interest in this area.

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