Comparison of Signaling Strategies for Multi Antenna Radar Systems

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ABSTRACT
A radar system is generally implemented and addressed to detect the target of concern. So, in a radar system, analysis and application of Ultra Wide Band (UWB) signals solves most of the problems of radar target detection. Since multiple-input multiple-output (MIMO) radar possess significant potentials for fading mitigation, resolution enhancement and interference and jamming suppression, by operating the MIMO radar with UWB signals it is expected that the resolution capability of the radar system improves significantly. These radars are generally called as Hybrid-MIMO radars. Due to the time resolution and the frequency dependence of the scattering centers over the potentially large bandwidth greater information can be obtained. The recent technological advances in radar's signal bandwidth given the radar performance can be improved by providing better range and measurement accuracy. The radar range resolution improves the target identification and tracking capability, improving radar immunity to passive interference. Finally radar countermeasure against narrowband electromagnetic signal interferences is enhanced. Using the vast advances and advantages of MIMO in communications and benefits of using UWB signals, this paper presents the investigation of Hybrid-MIMO radars. The simulation analysis has been carried out to demonstrate the promising features of these radars in terms of better target identification and improved transmit beampattern.

Keywords
Array processing, beamforming, beampattern design, dimensionality reduction, multiple-input multiple-output (MIMO) radar

1. INTRODUCTION
Recent works on MIMO Radar demonstrate enhanced target localization performance, dedicated to their increased degrees of freedom and use of arrays brought by the orthogonal transmitting signals [1-2]. This enhanced degrees of freedom is obtained from the utilization of orthogonal waveforms from multiple transmit/receive antennas which produces improved spatial resolution. This spatial resolution is greatly beneficial in angle estimation. Hybrid Radars are intended to determine the target coordinate in a cluttered environment [1-4]. SNR affects the reliability of detection and accuracy of estimation. The signal bandwidth affects many performance measures. Signal waveform affects detection, estimation and ambiguity [2]. The utilization of UWB signals improves the target resolution and accuracy of parameter estimation. Due to their large bandwidth UWB signals are less prone to passive interference and have a very low probability of intercept and unexceptional electromagnetic operation due to their low transmitting power. Hybrid radar has been a under research for a long time due to the various benefits it offers [3-5]. This paper investigates the use of UWB signals together with a spatially distributed multiple transceiver schemes in radar. Multiple signaling originate from the use of spatial diversity in communication systems.

In radar signal processing the diversity schemes in use are time diversity, frequency diversity, polarization diversity and space diversity. Spatially distributed multiple transceivers use is limited only in terms of the usage of more space for implementation, but information extraction from the target is improved by viewing the target from multiple angles. Coupling the multiple signaling scheme with UWB signals yields fine range resolution.

Radars have been developed that revolve around the main idea of exploiting the waveform diversity based on the array configurations used [7]. An array of radar elements is used with highly correlated signals to form a controllable beam, which can be adjusted in a certain direction to scan the desired space. These radars are called phased-array radars and the process is known as Spatial filtering [8].

Spatial filtering uses highly correlated signals at the radar antenna elements. Instead of spatial filtering, which views one aspect of the target at a time, MIMO radar [9-12] uses spatially distributed multiple transceivers. MIMO radar systems take advantage of the non-relativity of transmitted and received signals and also on the diversity of target by viewing the target from multiple aspects. With minutely changing the viewing angle causes large fluctuations in radar cross section (RCS) because the reflected energy depends largely upon the range as well as the receive look-angle of the target [2]. By maximizing the received energy in radars and appropriately combining the received signals could lead to better information from the target. Most of the theoretical models of MIMO radar have shown its advantages over traditional beamforming approaches [9-10].

This paper presents the results and analysis of Hybrid-MIMO radar. The target response was analyzed to compare MIMO radar with its variants. Results show that the Hybrid-MIMO radar [11]-[14] provides better target identification and over performs its counterparts showing the promise in this new architecture of radars. These results also give insight into why some channels of the MIMO radar systems perform better than the others. The aim of the experiments was to analyze initial measurements for Hybrid-MIMO radar in a non-multipath and much less dense scenarios making use of simple signal processing tools thereby establish the advantages achieved with Hybrid-MIMO radar. The initial experimental work has set the stage for investigation into unexplored and promising new radar architecture.

In Sections II and III the background for phased-MIMO radar and MIMO radar is presented. In Section IV, the mathematical equations pertaining to the matrix which contains the target parameters is formulated. Finally we propose a new method, Hybrid-MIMO radar, with the aim to improve the overall transmit beampattern. In Section V the simulation results show significant performance gains that are achieved by Hybrid-MIMO radar as compared to MIMO radar and phased-array radar.

2. PHASED-MIMO RADAR SIGNAL MODEL

Phased-MIMO radar is a new concept which tries to bring superior aspects of both phased-array and MIMO radar together in a single radar system. This radar system employs transmit and receive arrays which has closely spaced antenna elements like Coherent MIMO radar. Transmit array is partitioned into a number of subarrays that are allowed to overlap. Each subarray coherently transmits waveforms and performs beamforming towards a certain direction in space. By this way a coherent processing gain can be achieved like a phased-array radar system.

Consider a radar with $\mathrm{M_t}$ transmitting and $\mathrm{M_r}$ receiving antennas. If these are colocated then $\mathrm{M_t} = \mathrm{M_r}$. Let each of the transmit element, transmit a narrow band signal x(□). If a weight coefficient $\mathrm{w_{m,k}}$ is equal to zero, it means that the mth transmit element does not belong to kth subarray. The nonzero weight coefficients of a subarray scales the same waveform to form and steer a beam in space and the waveforms $\mathrm{x_m(t)}$ and $\mathrm{x_l(t)}$ are orthogonal when $m \neq l$. Now the coherent transmit processing vector is assumed to be

$$\mathrm{d}(\theta) \triangleq \left[\mathrm{w}_1^{\mathrm{H}}\mathrm{c}_1(\theta) \quad \cdots \quad \mathrm{w}_{\mathrm{k}}^{\mathrm{H}}\mathrm{c}_{\mathrm{k}}(\theta)\right]^{\mathrm{T}} \tag{1}$$

here $\mathrm{w_k}$ and $\mathrm{c_k}(\theta)$ is the beamforming vector and the steering vector related to the transmitter. The steering vector represents the phase delays associated with each transmit-receive pair. The diversity vector $\mathrm{b}(\hat{\theta})$ can be written as

$$\mathbf{b}(\hat{\theta}) = \begin{bmatrix} 1 \\ e^{i2\pi d sin\theta/\lambda} \\ \vdots \\ e^{i2\pi d(M_t-1)sin\theta/\lambda} \end{bmatrix} \tag{2}$$

here λ is the radar carrier wavelength.

In the far field, for a stationary target of the corresponding antenna array located in the direction θ, the total signal at the target location, assuming a non-dispersive propagation can be given as

$$\mathrm{x}(t) = \mathrm{b}^{\mathrm{H}}(\boldsymbol{\theta})\mathbf{x}(t-\tau_t) \tag{3}$$

$$= \mathrm{b}^{\mathrm{H}}(\boldsymbol{\theta})\mathbf{b}(\theta)s(t-\tau_t) \tag{4}$$

$\mathbf{b}(\theta)$ is defined in (2) with $\hat{\theta}$ replaced by θ. τ_t is the time taken by a signal reach the target that is transmitted by receiver. Consider the vector model of phased-array radar in a beamformer $\mathrm{x}(t) = \mathbf{b}(\theta)s(t)$. This gives the array output vector as a function of time. This output vector depends upon the signal and the response of the array to the signal. To form a beam we need a beamformer which produces the weighted sum, so the virtual data vector is given as

$$y \triangleq [\mathrm{x}_1^T \quad \cdots \quad \mathrm{x}_M^T]^T$$

$$= \sqrt{\frac{M_t}{L}}\beta_t \mathrm{v}(\theta_t) + \sum_{j=1}^{C}\sqrt{\frac{M_t}{L}}\beta_j \mathrm{v}(\theta_j) + n \tag{5}$$

here $\mathrm{v}(\theta)$ is the steering vector and n is the noise term. By properly designing the beamformer weight vector we can steer the beam in the desired direction. Now if L=1 then only one wave is emitted, where the complete transmitted array is taken as one subarray. Therefore the below equation (6) gives the signal model for the phased-array radar

$$y = \sqrt{M_t}\beta_t \mathrm{v}(\theta_t) + \sum_{j=1}^{C}\sqrt{M_t}\beta_j \mathrm{v}(\theta_j) + n \tag{6}$$

Similar to transmit beamforming, weight coefficient may also be used at the receiver to enable the system perform beamforming at the receiver since coherent processing becomes possible for phased-MIMO radar.

3. MIMO RADAR

The aim of radar signal processing is to estimate the parameters of the channel. MIMO means any radar system that examines a channel by transmitting independent waveforms and receive those waveforms with some specific signal processing. Consider a radar with M_t transmitting and M_r receiving antennas. Both the antenna arrays are assumed to be near to each other in space so that they see targets at same directions. To satisfy the orthogonality condition

$$\int_{T_0} \boldsymbol{\varphi}(\mathbf{t})\boldsymbol{\varphi}^{\mathbf{H}}(\mathbf{t})dt = \mathbf{I}_{M_t} \tag{7}$$

where T_0 is the radar pulse width, $\mathbf{I}_{M_t}$ is the M_t x M_t identity matrix.

The receive array vector can be designed as

$$\mathrm{x}(t) = \mathrm{x}_t(t) + \mathrm{x}_j(t) + n(t) \tag{8}$$

where $\mathrm{x}_t(t)$, $\mathrm{x}_j(t)$ and $n(t)$ are the target signal, jamming and noise components. The target signal can be represented by

$$\mathrm{x}_t(t) = \beta \mathrm{a}^{\mathrm{T}}(\theta_t)\boldsymbol{\varphi}(\mathbf{t})\mathrm{b}(\theta_t) \tag{9}$$

Finally the virtual data vector can be represented as

$$y \triangleq [\mathrm{x}_1^T \quad \cdots \quad \mathrm{x}_M^T]^T$$

$$= \beta\mathrm{a}(\theta_t)\otimes\mathrm{b}(\theta_t) + y_{j+n} \tag{10}$$

where y_{j+n} is the interference-plus-noise component.

At the transmit/receive arrays of the radar system conventional nonadaptive beamforming is used. The expressions for the transmit/receive beampattern are derived. The phased-MIMO radar beampattern expressions and the analogous expressions of the phased-array and MIMO radars are analyzed. The beamformer weight vectors for conventional uplink beamforming as all subarrays have equal aperture, are given by

$$\mathbf{u}_k \triangleq \frac{\mathrm{a}_k(\theta_t)}{\|\mathrm{a}_k(\theta_t)\|}, k = 1,\ldots.K \tag{11}$$

where $\mathrm{a}_k(\theta_t)$ is the steering vector associated with the k^{th} subarray.

We apply the conventional beamformer to the virtual array at the receiver, therefore, the receive beamformer weight vector is given by

$$\mathbf{u}_i \triangleq \mathrm{v}(\theta_t) = \mathrm{d}(\theta_t)\odot b(\theta_t)\otimes a(\theta_t) \tag{12}$$

Let $\mathrm{G}(\theta)$ be the normalized radar beampattern, that is

$$\mathrm{G}(\theta) \triangleq \frac{\left|\mathbf{u}_i^H \mathrm{v}(\theta)\right|^2}{\left|\mathbf{u}_i^H \mathrm{v}(\theta_t)\right|^2} \tag{13}$$

4. HYBRID MIMO MATRIX FORMULATION

For the measurement of the matrix parameters, waveforms should be orthogonal in order to separate each pair of transmitter/receiver. Thus, waveform design is a considerable issue associated with MIMO Radar [5]. Here, signal separation has been exploited to enable the scattering matrix elements M_{ij}. The signals received from N_t transmitters can be expressed in frequency domain by applying appropriate transforms as:

$$F_R = \sum_{i=0}^{N_t-1} [M].F_i + N_G \qquad (14)$$

where N_G is the additive Gaussian noise, F the Fourier transform of transmitted signals, M the scattering matrix that contains the probed channel information and expressed as:

$$(M)_{mn} \propto e^{(-ik.(x_m+y_n).d.\sin(\theta_0))} \qquad (15)$$

where θ_0 refers to the signal bearing estimation while considering the target at far-field distance from the radar system and k the wave number. This channel matrix contains information referring to the target parameters. After estimation of the channel matrix, a beamforming in time domain algorithm is performed to detect the target position.

5. SIMULATION RESULTS

In our simulations, we assume a uniform linear array(ULA) for the transmitting and the receiving end with T = 10 antennas used for transmitting the baseband waveforms uniformly in all directions and a ULA of R = 10 antennas spaced half a wave length between each antenna at the receiving end uniformly in all directions. The additive noise is designed such that the complex Gaussian zero-mean white random sequence has identical variances in each array sensor. We assume two interfering targets located at directions -30^o and 30^o where in one it has spatially distributed interference. The target of interest is assumed to reflect a plane-wave that impinges on the array from direction $\theta_t = 10^o$.

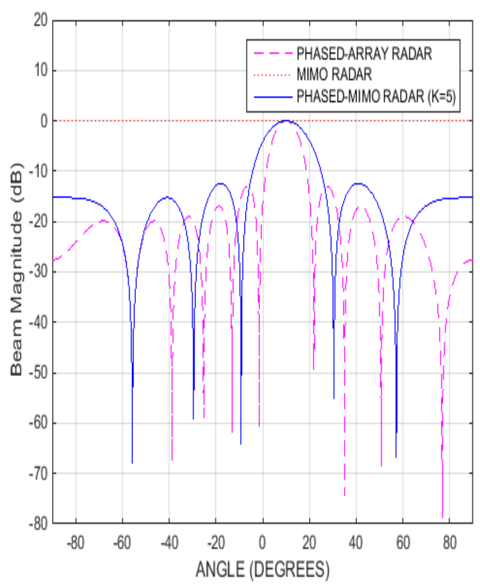

Fig. 1. Transmit beampatterns using conventional beamformer ($d_T = 0.5$ wavelength).

In some of our simulations we compare phased-MIMO radar (5) with the phased-array radar (6) and the MIMO radar (10), while in other simulations we compare phased array radar with the MIMO radar and the Hybrid-MIMO radar (14)-(15).

For the phased-MIMO radar, we always used K=5 subarrays which are assumed to be fully overlapped. We compare different radar techniques to each other in terms of their transmit/receive beampatterns (11)-(13).

We have considered the case where the transmit antennas are located half a wavelength apart, i.e $d_T = 0.5$ wavelength. It can be observed that MIMO radar achieves omnidirectional beampattern whereas phased-array achieves high directional gain with narrow main lobe. Figs. 1 and 2 show the transmit beampatterns and the waveform diversity beampatterns of phased-array, MIMO and phased-MIMO configurations, respectively, whereas in Fig. 3 the overall transmit/receive beampatterns for the same techniques are shown.

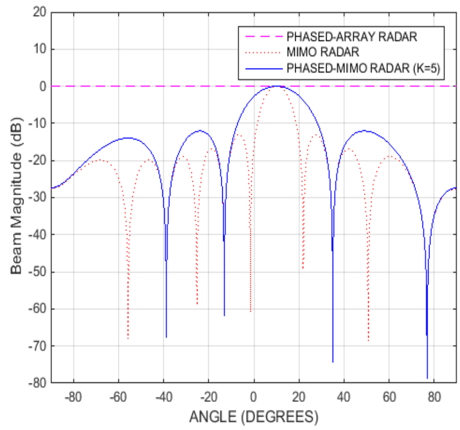

Fig. 2. Waveform diversity beampatterns using conventional beamformer ($d_T = 0.5$ wavelength)

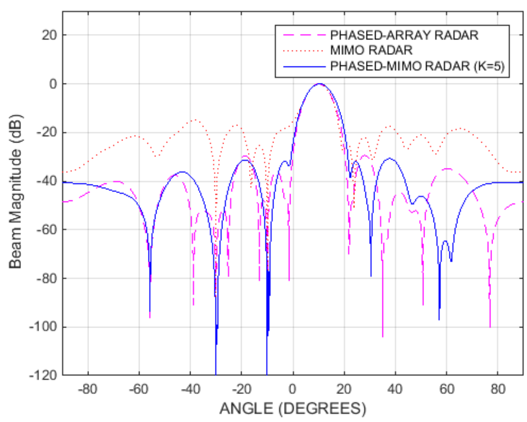

Fig. 3. Overall beampatterns using conventional transmit/receive beamformer ($d_T = 0.5$ wavelength).

From Fig. 2 the phased-array radar has no waveform diversity gain whereas the waveform diversity beampatterns of the MIMO radar and phased-MIMO radar are similar to the conventional beampatterns. It can be observed that the phased-MIMO radar has wider main lobe and sidelobe levels when compared to the diversity patterns of the MIMO radar.

In Fig. 3 the overall transmit/receive beampattern for phased-MIMO radar has been considerably better than the beampatterns of phased-array and MIMO radars. Also the sidelobe levels of the phased-MIMO radar are lower than the sidelobe levels of the phased-array and MIMO radar.

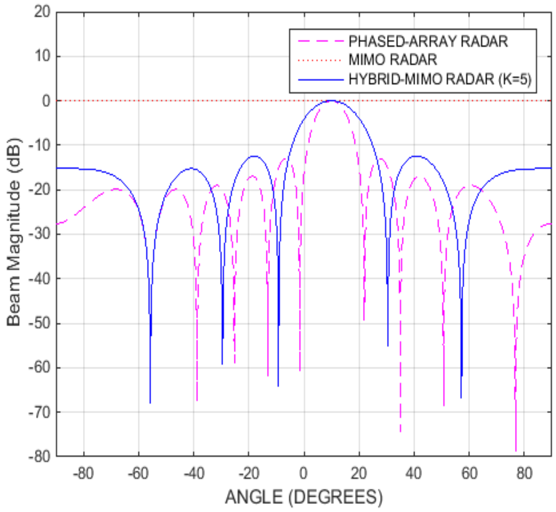

Fig. 4. Transmit beampatterns using conventional beamformer ($d_T = 0.5$ wavelength) with the combination of HYBRID-MIMO.

Fig. 4 shows the omnidirectional beampattern of MIMO radar whereas phased-array achieves high directional gain with narrow main lobe. The beampattern of the Hybrid-MIMO radar has a wider main beam and a slightly higher sidelobe level as compared to the beampattern of the phased-array radar.

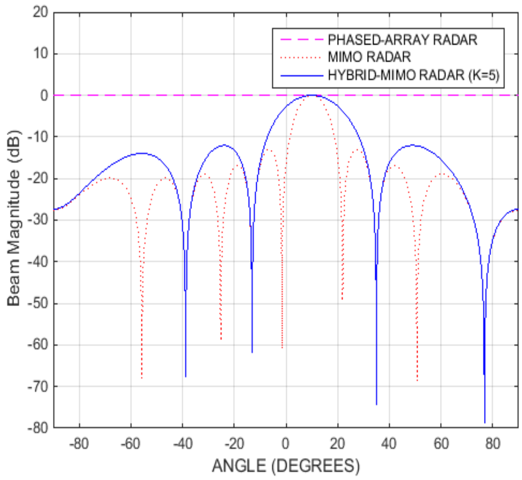

Fig. 5. Waveform diversity beampatterns using conventional beamformer ($d_T = 0.5$ wavelength) with the combination of HYBRID-MIMO

In Fig. 5 the phased-array radar has a flat gain whereas the waveform diversity gain of the Hybrid-MIMO radar is higher than the diversity gain of the MIMO radar.

From Fig. 6 it can be observed that the proposed Hybrid-MIMO Radar has lower sidelobe levels as compared to the MIMO and phased-array radar.

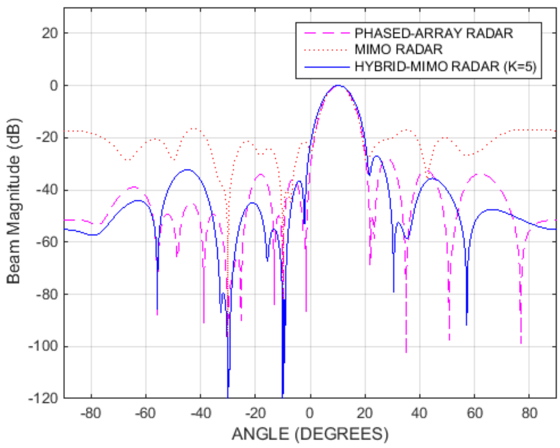

Fig. 6. Overall beampatterns using conventional transmit/receive beamformer ($d_T = 0.5$ wavelength) with the combination of HYBRID-MIMO.

However the proposed Hybrid-MIMO radar is shown to offer much better overall performance. From the comparisons of Fig. 3 and Fig. 6 we conclude that the overall beampatterns for Hybrid-MIMO radar has been exceptionally higher than the phased-MIMO radar.

6. CONCLUSIONS

A new technique for MIMO radar with UWB antennas has been proposed. The subarrays are mixed together to form a MIMO radar system resulting in higher angular resolution capabilities. It is shown that the Hybrid-MIMO technique outdoes the advantages of the phased-array and MIMO radars and, therefore, it has a superior performance. Simulation results confirm, that the theoretical observations demonstrate the effectiveness of the proposed Hybrid-MIMO radar technique. It is noted that the beam width and the side lobe attenuation has remarkably enhanced using the proposed Hybrid-MIMO radar. Using Hybrid-MIMO radar for the given simulation scenario the beamwidth obtained is 8.5^o using 3dB beamwidth measurement standards, whereas in phased-MIMO radar it is 8.2^o, whilst enhancing the range of effective radiated power and improving the target tracking capability. An approximate 20dB side lobe attenuation improvement is observed using Hybrid-MIMO radar when compared to phased-MIMO radar, which results in improved transmit beampattern. The formulation of the new Hybrid-MIMO radar technique opens a new avenue in MIMO radar developments. Some new problems highlighted in the paper are the transmit beamforming and transmit subarray waveform designs, which satisfy certain desired properties. Investigation of other characteristics like directivity, antenna gain, etc remains as future scope.

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