Diversity employment into target plus clutter SAR imaging using MIMO configuration

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Abstract— **Multiple Input Multiple Output (MIMO) configurations in radar systems provide architectural and performance advantage over conventional monostatic and bistatic systems due to the implicit diversity characteristics of any MIMO system. Various authors are individually addressed either of these diversities. This work aims at parameterizing all the three, spatial, frequency and waveform diversities and hence designing a new MIMO SAR system for high resolution achievement. This system is designed taking into account both target and clutter, as clutter background pollutes the images substantially. The parameterizations and hence the constraints obtained on the system architecture and transmit signal properties ensure high resolution and better performance over conventional SAR imaging systems.**

I. INTRODUCTION

Multiple input multiple output (MIMO) radar systems have gained popularity and attracted attention of late for their ability to enhance system performance. In many ways MIMO radar is similar to MIMO communication system. Among the many possible uses of a radar system, tracking and detecting targets, estimating target model parameters and creating images of targets (SARs) are some of the most common. Various authors have shown how MIMO radar enhances the performance [1-3].

Over the past few years various new MIMO radar techniques have been developed for target detection, tracking and also for SAR imaging. The concept of diversity for a general MIMO system is discussed widely and several methods to improve the performance have been reported. From all the analysis carried out so far, three types of diversities can be identified: spatial diversity - imposing architectural constraints on transmitter and receiver [3-4], waveform diversity - identifying several types of signals for transmission [5] and frequency diversity - spectrally separating information to be gathered [6]. Some of these have been widely discussed and system structures have been designed meeting this improved performance. Lehmann et. al. have shown that coherent processing of signals has better resolution than for non coherent processing [7]. Antonio et. al. show that orthogonal input signals track the target better than coherent input signals [8]. Spatial diversity parameter has been discussed by Lehmann et. al [3]. Angular diversity strategies are discussed by Fishler et. al. [4]. Our previous work included combining all these abstract ideas of the three different diversities and design a new hybrid strategy for radar target detection and tracking [9]. This paper deals with analyzing MIMO strategy in radar imaging and develop the theory and parameterizations essential for the inclusion of spatial, frequency and waveform diversities. We now, hence, address the problem of designing a hybrid strategy for radar imaging using a diversified MIMO configuration.

The remainder of this paper is organized as follows. Section II introduces the general radar imaging problem and deals with the notation used here. Section III parameterizes the spatial and frequency diversity and develops the necessary constraints on the system. Section IV addresses the waveform diversity problem. Section V discusses this newly developed design and concludes the paper.

II. RADAR IMAGING PROBLEM

In radar imaging problems the target is a region instead of a single object, hence we say the region to be imaged at some single instant has object at its beam pointing direction and the surrounding region in its clutter. Note that in radar imaging this clutter problem results in side lobe energy [10] and hence both target (object) and clutter are of importance here. The transmitting signals along with the system architecture should help in reducing this side lobe amplitudes compared to main lobe resolution. This is the aim of any good radar imaging system. Now we consider a system with MIMO configuration, having M transmitters and N receivers. Considering the target as a 2D region, transmit waveforms will be sent from these M transmitters and they are scattered by the target and depending on the position of the receiver block, the N receivers receive the target scattered signals. In general the analysis of any system is done with impulse spectrum inputs, the same is followed here and the theory we develop is firstly based on considering the target as a single point scatterer. Multi scatterer issue will be addressed later.

With the description of the radar imaging system under consideration, we try to fix the number of transmitters and receivers alone and apply the diversity principles, so that we arrive at constraints on the transmit - receive system architecture and transmit signal properties. This design strategy relates to Space-Time Adaptive Processing (STAP) of signals [10]. The next section deals with employing spatial and frequency diversity into the system architecture, so that once a spatial - frequency diverse radar imaging platform is designed, the beamformers of the transmit block can be constructed to maximize the final SINR ratio of the reception point (the receiver block) and parallely to minimize the side

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lobe energies. This ensures constraints on the transmit signal properties hence making the system a waveform diverse one, apart from it already being a spatial - frequency diverse system.

We first give an overview of spatial and frequency diversity constraints and apply them onto the system, in the following section. Later we move on to the waveform diversification as discussed above..

III. SPATIAL AND FREQUENCY DIVERSITY EMPLOYMENT

A. Virtual array and Spatial diversity

In a MIMO system we have multiple transmitters and receivers. Consider the position of m^{th} transmitter and n^{th} EQ y\s\do5(R\,m) respectively. We then have the steering vectors of both transmitter and receiver as **Error!**and **Error!** respectively where u^T and u^R are the unit vectors pointing from transmitter to target and receiver to target respectively.

The net steering vector from the received signal format will be [10]

EQ [e\s\up5(j \F(2π,λ)u\s\up4(TR)(x\s\do4(T\,m)+x\s\do4(R\,m)))]\s\up5(T) (1)

which shows that if the transmit steering vector has M elements from 0 to $M-1$ and receive counterpart has N elements from 0 to $N-1$ then the net steering vector of the system will have NM elements. We call it the NM element virtual array. It is as if the net system spatial configuration can be seen as convolution of transmit and receive spatial elements which explains the extra spatial dimension given by space-diverse MIMO. A system with M and N individual spatial elements (transmitter and receiver positions are independent) will replicate itself to a system with a total of NM monostatic transmitters. Fig. 1 shows the illustration of this virtual array concept with combination of several transmitter and receiver blocks. We here note that again with combinations of spatial orientation of transmitter and receiver blocks and new structure can be observed, an indication of spatial diversity.

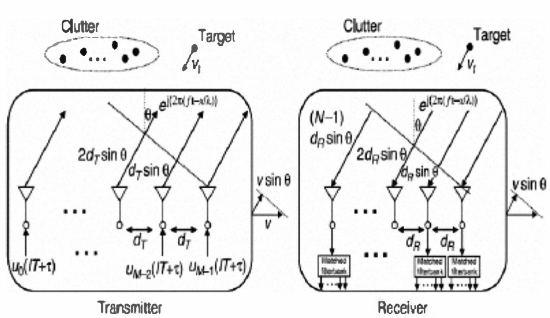

Fig 1. MIMO radar system with M transmitters and N receivers showing virtual array concept

This virtual array concept helps immensely in parameterizing the spatial and frequency diversity aspects. We first introduce the frequency diverse system configuration and later proceed to parameterizations.

B. Frequency diverse MIMO system

We know that the reflectivity of any target is dependent on the frequency of the signal incident on it. Using this we can explore the frequency diversity aspect of the system [11, 12]. Consider the system structure where the transmitter block has some fixed number of transmit elements. Now instead of sending a single input transmit signal from each of this EQ f\s\do5(1)\,f\s\do5(2)\,....\,f\s\do5(N\s\do4(f))and pass N_f EQ s\s\do5(1)\,s\s\do5(2)\,....\,s\s\do5(N\s\do4(f)) from each of them so that the net signal from m^{th} transmitter is

$$X_m = \sum_{p=1}^{p=N_f} \alpha_{pm} s_p e^{j2\pi f_p t} \quad (2)$$

where α_{pm} is the weight of signal from p_{th} frequency level in m_{th} transmitter. Fig. 2 shows the explicit structure of a frequency diverse MIMO system. Intuitively the virtual array concept engulfed the spatial diverse nature of the system, as shown in the previous section and over it this multi carrier frequency strategy has made it frequency diversified.

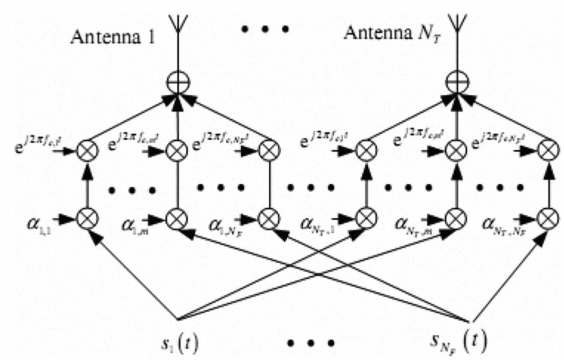

Fig 2. MIMO radar system with M transmitters employing frequency diversity. *Nf* number of different frequency bands are employed onto the transmitter block.

Note that a MIMO system with M transmitters, N receivers and N_f carrier frequencies is equivalent to a monostatic phased array system with NMN_f transceivers [10]. At this point the system is a spatial - frequency diverse one, we now go into analyzing the signal and beam former structures so as to gain insight into the transmit signal waveform structure.

IV. SIGNAL AND BEAMFORMER DESIGN

A. Signal Design

We next come to parameterizing the two diversities introduced in the system so far and design transmit waveforms for them, which allows us to employ waveform diversity into the system. Our final aim is to get design constraints from these diversity implementations and hence use them along with best beamformer design to achieve a system with high performance, of course here both target and clutter are important for complete analysis.

Considering the final system as described in the previous section, and baseband signal as a multi-pulse sequence, we have the signal coming from transmitter block given by

$$X(lT+\tau)=\sum_{m=0}^{M-1}\sum_{p=1}^{p=N_f}\alpha_{pm}s_p(\tau)e^{j2\pi f_p(lT+\tau)} \quad (3)$$

where T is the pulse repetition period, τ is the intra pulse time and l is the sample index. This signal reaches target and as we have already discussed the reflection coefficient (RCS) is frequency dependent allowing us to write the reflected signal from target with target reflection amplitude $\square_{t;p}$ for f_p as [12], where the notation used is, r: range distance from transmitter; $\square_{i;p}$: clutter reflection amplitude; Θ_t: target reception angle; Θ_i : clutter reception angle; N_c: number of clutter scatterers; V: horizontal speed of radar platform; V_t: velocity component of target along the vector pointing from target to transmitter; d_T: inter transmitter sub array distance; d_R: inter receiver sub array distance; and $y_n^{(J)}(lT+\tau+\frac{2r}{c})$, $y_n^{(W)}(lT+\tau+\frac{2r}{c})$ are jammer and noise signals received. After match filtering with baseband wave forms $s'_p(t)$ we have the received signal at the p^{th} slot of n^{th} antenna,

EQ y\s\do5(n\,p\,l)= \i \su(m=0,M−1,)□\s\do5(t\,p)α\s\do5(pm)e\s\up5(j2πf\s\do4(s;p)(n+γm))e\s\up5(j2πf\s\do4(D;p)l)+
EQ + \i \su(i=0,N\s\do5(c)−1,) \i \su(m=0,M−1,)□\s\do5(i\,p)α\s\do5(pm)e\s\up5(j2πf\s\do4(s\,i;p)(n+γm+βl))e\s\up5(j2πf\s\do4(D;p)l)+y\s\up((J),n\,p\,l)+y\s\up((W),n\,p\,l)

5(R)) and **Error!**. **Error!**, **Error!** and **Error!** represent the normalized spatial and Doppler frequencies. Note that all these three parameters are constrained to region, say $[-W_f, W_f]$ for a EQ y\s\do5(n\,p\,l)is a NN_fL vector, call $\square_{t;p}\alpha_{pm}=\Delta_{pm}$ and $\square_{i;p}\alpha_{pm}=\Delta'_{pm}$.

B. Frequency Characteristics

Once the received signal has been constructed with system spatial architecture as discussed in the previous section, we now discuss the issue of determining the carrier frequencies from these system parameters. We show that these frequencies depend only on the geometry of system and are independent of transmit waveforms of target properties (range, speed, etc.). From the received signal format we see that target and clutter responses are dependent of frequencies f_p, hence consider $y^{(TC)}$, the target-clutter response of system. Previous work on frequency diversity of phased array radar has shown that we can achieve side lobe reduction and decorrelation with suitable choice of f_p [12, 13]. With out loss of generality we say

$$f_p = f_0+(p-1)\Delta f,\ p=1,2,\ldots N_f$$

and for simpler analysis purpose we use a single pulse case instead of a multi-pulse one i.e. l=0. At the 0^{th} index receiver antenna, beampattern can be given by

$$B_p=\sum_{m=0}^{M-1}e^{j2\pi\frac{d_R\gamma m}{c}f_p\sin\Theta_t}+\sum_{m=0}^{M-1}\sum_{i=0}^{N_c-1}e^{j2\pi\frac{d_R\gamma m}{c}f_p\sin\Theta_t} \quad (4)$$

where transmit signal amplitudes α_{pm} are taken as unity $\square p,m$, for computational convenience. At any single instant of time the radar must capture target and blur out clutter from reception which boils out as to decorrelation of target and clutter responses at sometime t. So for further analysis the clutter reception angle should be taken as a combination of target reception with some additive random noise, i.e. $\Theta_i=\Theta_t+d\Theta_i$ with $d\Theta_i$ representing the clutter reception disturbance. From trigonometry, we have

$$\Theta_i=\Theta_t+d\Theta_i \sin\Theta_i\approx\sin\Theta_t+d\Theta_i\cos\Theta_t \quad (5)$$

Considering the mean of $d\Theta_i$ to be zero, we then have

$$B_p=\sum_{m=0}^{M-1}e^{j2\pi\frac{d_R\gamma m}{c}f_p\sin\Theta_t}[1+N_c] \quad (6)$$

If the measuring azimuth angle is taken as Θ, the measuring beam pattern is approximated as

$$F_p(\Theta)=\sum_{m=0}^{M-1}e^{j2\pi\frac{d_R\gamma m}{c}f_p(\sin\Theta_t-\sin\Theta)}=\sum_{m=0}^{M-1}e^{j2\pi\frac{d_R\gamma m}{c}f_p(\psi_t-\psi)} \quad (7)$$

ψ= \F(2πd\s\do5(R)γmsinΘ,c). The auto correlation **Error!** is then

EQ R\s\do5(p\,p+1)=EF\s\do5(p)(Θ)F\s\do5(p+1)(Θ)=Msinc[Δf(ψ\s\do5(t)−ψ)/2] (8)

This gives the decorrelated beampattern of this system. Now for calculation of Δf we fix the azimuth of observation Θ, which gives

(p\,p+1)=Msinc(Δfψ/2) (9)

Now for complete decorrelation on sidelobes we need, with ambiguity of k,

EQ \F(Δfψ\s\do5(t),2)=kπ\,k=1\,2\,....(10)

$$i.e. \Delta f=\frac{2k\pi}{\psi_t}0\square\Delta f=\frac{ck}{d_T m\sin\Theta_t} \quad (11)$$

and to avoid aliaizing we require $f_p\square\Delta f$.

Now with this constraint on choosing frequency ranges of transmit signals, the system will have all the frequency diversity characteristics we discussed earlier. Already the system construction has been made keeping in mind the spatial diversity inclusion. Now we arrive at the question of how best to design the transmit waveforms with these spatial and frequency diversities already incorporated

C. *Waveform Design*

EQ α\s\do5(*pm*)=α\s\do5(*p*)□*p*\,*m*, then we get the clutter response at the receiver as

EQ *y*\s\up((*c*),*n*\,*m*\,*l*)= \i \su(*p*=1,*N*\s\do5(*F*),) \i \su(*i*=0,*N*\s\do5(*c*)−1,)□\s\do5(*i*\,*p*)α\s\do5(*p*)*c*\s\do5(*i*\,*p*\,*n*\,*m*\,*l*) (12)

EQ *c*\s\do5(*i*\,*p*\,*n*\,*m*\,*l*)=*e*\s\up5(*j*2π*f*\s\do4(0)ε\s\do4(*i*)(*n*+γ*m*+β*l*))*e*\s\up5(*j* 2π(*p*−1)Δ*f*ε\s\do4(*i*)(*n*+γ*m*+β*l*)) (13)

Combining all the $c_{i,p,n,m,l}$'s into one $c_{i,p}$ for all *n,m,l* we can write

EQ *y*\s\up5((*c*))= \i \su(*p*=1,*N*\s\do5(*F*),)α\s\do5(*p*) \i \su(*i*=0,*N*\s\do5(*c*)−1,)□\s\do5(*i*\,*p*)*c*\s\do5(*i*\,*p*)= \i \su(*p*=1,*N*\s\do5(*F*),)*y*\s\up((*c*),*p*) (14)

i.e. writing $A=[\alpha_1\alpha_2....\alpha_{N_F}]^T$ and $Y^{(C)}=[y_1^{(c)}y_2^{(c)}....y_{N_F}^{(c)}]^T$ the target free signal (the clutter + jammer + white noise signal) at the receiver is

$$y^{(CJW)}=A^TY^{(C)}+Y^{(J)}+Y^{(W)} \qquad (15)$$

from which we get

$$R^{(CJW)}=A^TY^{(C)}Y^{(C)^{\square}}A^H+R_{JW} \qquad (16)$$

with R_{JW} representing the jammer+noise covariance matrix. Here $Y^{(C)^{\square}}$ is the complex conjugate of $Y^{(C)}$ and A^H is the Hermitian transpose of A. Jammer and noise power are independent and $R_W=\sigma^2 I$. Hence $R_{JW}=R_J+R_W$ where R_J is the jammer autocorrelation matrix, constant once a jammer is fixed. The target free signal has to be as minimum as possible at the receiver, using this condition we can transform the above equation into a minimization problem;

EQ □*A*\s\up5(*T*)*b*=1;*A*\s\up5(*T*)=[α\s\do5(*pm*)]□*p*\,*m*

This minimization problem on the covariance matrix of target free signal will give the required transmit design parameters. This completes the parameterizations of the clutter+target detection with all three spatial, frequency and waveform diversities employed into the system.

V. Discussion

MIMO configurations for radar target detection, tracking and imaging are being widely discussed for the architectural and performance advantages that they are proving. This paper addresses a radar imaging system with MIMO configuration, by employing spatial, frequency and waveform diversities into the transmitter - receiver architecture and transmit signal structures. These three diversities are completely parameterized and employed into the system. The future work aims at developing the waveforms according to the constraints derived here and testing real time target data using this new hybrid system.

Acknowledgment

The work has been funded by the Department of Science and Technology (DST), India through their fast track research program, via sanction number SR/FTP/ETA-34/2007.

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