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Signal Processing Algorithm of Space Time Coded Waveforms for Coherent MIMO Radar: Overview on Target Localization

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ABSTRACT: *Space-time coding (STC) has been shown to play a key role in the design of MIMO radars with closely spaced antennas. Multiple-input–multiple-output (MIMO) radar is emerging technology for target detection, parameter identification, and target classification due to diversity of waveform and perspective. First, it turns out that a joint waveform optimization problem can be decoupled into a set of individual waveform design problems. Second, a number of mono-static waveforms can be directly used in a MIMO radar system, which offers flexibility in waveform selection. We provide conditions for the elimination of waveform cross correlation. However, the mutual interference among the waveforms may lead to performance degradation in resolving spatially close returns. We consider the use of space–time coding (STC) to mitigate the waveform cross-correlation effects in MIMO radar. In addition, we also extend the model to partial waveform cross-correlation removal based on waveform set division. Numerical results demonstrate the effectiveness of STC in MIMO radar for waveform de-correlation. This paper introduces the signal processing issued for the coherent MIMO radar without and with STC waveforms and also studied signal processing algorithms of coherent MIMO radar with STC waveforms for improvement of target detection and recognition performance for real life scenario.*

Keywords: *STC, coherent, Probability detection, MIMO and SNR.*

I. INTRODUCTION

Traditional MIMO radar [1]-[2] takes the opposite direction of the phased-array radar. The approach is to employ multiple uncorrelated waveforms that are radiated via omnidirectional transmission, in compare to phased-array radar [3], where a single probing waveform is sent via directional transmission. Inspired by several publications have advocated the concept of MIMO radar from the system implementation point of view, processing techniques for target detection and parameter estimation. Target parameters of interest in radar systems include target strength, location, and Doppler characteristics. MIMO radar systems employ multiple antennas to transmit multiple waveforms and engage in joint processing of the received echoes from the target. MIMO radar may be configured with its antennas co-located or widely [4] distributed over an area and able to provide independent diversity paths. The co-located MIMO [5], [6] radar where the transmitter and the receiver are close enough so that they share the same angle variable, i.e., coherent MIMO radar.

STC for waveform design has been introduced in [7] and [8] to cope with detection under possibly correlated clutter and, more generally, to introduce a further degree of freedom at the transmitter side. It is a revolutionary development for exploiting the MIMO channel by using antenna array processing technology, which is currently stimulating considerable interest across the wireless industry. The STC ‘concept’ builds on the significant work by Winter’s in the mid-80’s which highlighted the importance of antenna diversity on the capacity of wireless systems [9]. The use of multiple antennas at both the transmitter and receiver is essential for the STC concept to work effectively , since STC exploits both the temporal and spatial dimensions for the construction of coding designs which effectively mitigate fading (for improved power efficiency) and are able to capitalise upon parallel transmission paths within the propagation channel (for improved bandwidth, efficiency).

In this paper, the problem of target detection in co- located MIMO radars is considered. A pulse-train signalling [10] is assumed to be used in this system. STC [12] is a MIMO technique that is designed for use with multiple transmitter antennas. This technique introduces temporal and spatial correlation into signals transmitted from different antennas. The intention is to provide diversity at the receiver and coding gain over an uncoded system without sacrificing the bandwidth.

The other MIMO technique is spatial multiplexing in which different data streams are transmitted from multiple antennas. In [11], a pulse-train signalling for co-located MIMO radars has been proposed. The received signal modelling and problem formulation is presented. It is shown that due to unknown values of Doppler frequency and target Direction of Arrival (DOA), a compound hypothesis testing problem is confronted. The standard technique for compound hypothesis tests when the Probability Distribution Function (PDF) of the unknown parameters is not known is the Generalized Likelihood Ratio (GLR) detection.. Full exploitation of these potentials can result in significant improvement in target detection, parameter estimation, target tracking and recognition performance. This motivates the authors MIMO radar using pulse-train signalling. Thus, each orthogonal waveform carries independent information about the target; spatial diversity about the target is thus created. Exploiting the independence between signals at the array elements, MIMO radar achieves improved detection performance and increased radar sensitivity.

II. COHERENT MIMO RADAR

Coherent MIMO radar uses antenna arrays for transmitting and receiving signals. These arrays may be co-located and even transmit and receive functions can be performed by the same array or the arrays may be separated. The separation between the elements may be uniform or non-uniform. The arrays can be filled or sparse depending on the application type.

But the separation is always small compared to the range extent of the target. Whatever the separation between the array elements is, the important point in coherent MIMO radar is that the array elements are close enough so that every element sees the same aspect of the target i.e. the same RCS. As a result, point target assumption is generally used in coherent MIMO radar applications.

A. System Model

Consider a coherent MIMO radar system that has transmit and a receive array consisting of M and N elements respectively. Then the received signal can be written as

$$y(t) = \sqrt{\frac{E_t}{M}}\mathrm{H}x(t-\tau) + w(t) \ldots \ldots (1)$$

Where, $\sqrt{E_t/M}\, Hx(t-\tau)$ denote the discrete time baseband signal transmitted by the transmit antenna elements where $x(t-\tau)$ is the input message signal with delay time, E_t is the total average transmitted energy and $w(t)$ is the noise vector.

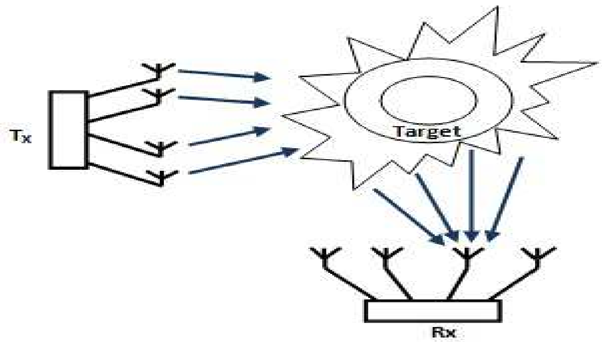

Fig.1. Coherent MIMO radar configuration.

B. Probability detection

The detection problem here can be formulated as binary hypothesis testing problem as follows:

$$\left.\begin{aligned} H_0 &: \bar{y} = \bar{w} \\ H_1 &: \bar{y} = \sqrt{\frac{E_t}{M}}\bar{\alpha} + \bar{w} \end{aligned}\right\} \ldots\ldots\ldots (2)$$

Where H_0 indicates absence of signal and H_1 indicates presence of signal.
It is well known that the optimum solution to this hypothesis testing problem under Neyman-Pearson criterion is the Likelihood Ratio Test (LRT).
The likelihood ratio test becomes,

$$\|\bar{y}\|^2 \underset{H_0}{\overset{H_1}{\gtrless}} T' \ldots\ldots\ldots (3)$$

To see the performance limit of coherent MIMO radar, the vector α become identical and coherent integration of the received samples becomes possible before detection process. The modified binary hypothesis testing problem turns in the form,

$$\left.\begin{aligned} H_0 &: \quad y = w \\ H_1 &: \quad y = \sqrt{\frac{E_t}{M_t}} MN\alpha + w \end{aligned}\right\} \ldots\ldots\ldots (4)$$

Where $\boldsymbol{w}$ is now a complex number.
The probability of false alarm rate, P_{fa} can be calculated as,

$$P_{fa} = Prob\left\{exp\left(\frac{1}{MN\sigma_w^2}\right) > T'\right\}$$
$$= exp\left(\frac{T'}{MN\sigma_w^2}\right) \ldots\ldots (5)$$

Then P_d can be written in terms of SNR and probability of false alarm rate as,

$$P_d = exp\left(\frac{ln(P_{fa})}{(SNR)N+1}\right) \ldots\ldots (6)$$

So, the probability of detection does not depend on the number of transmit antennas but depends only on number of receive antennas and SNR.

C. Results and Observation

To compare with the detection performance of Coherent MIMO Radar, the detector in (6) is implemented. P_{fa} value is set to 10^{-6}. If the number of receive elements is held constant at the value of 5, and the number of transmit elements is increased, the P_d vs SNR curve in Fig. 2 is obtained.

The graphics in Fig. 2 show that the detection performance does not change with increasing M. This is because the transmitted power is normalized and it does not change with the number of transmit elements, and also because the noise power and the signal power in the received signal after coherent summation increase at the same rate.

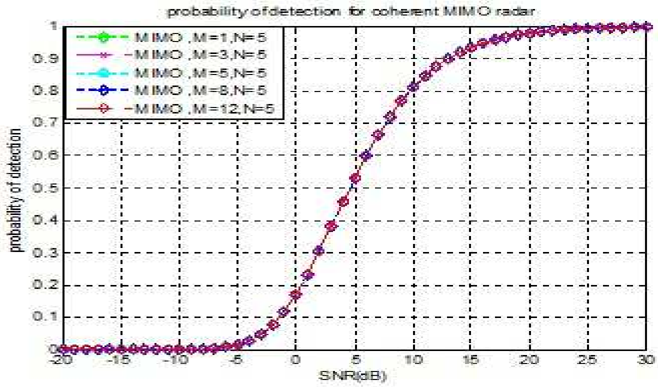

Fig. 2. Probability of detection for coherent MIMO radar, changing M

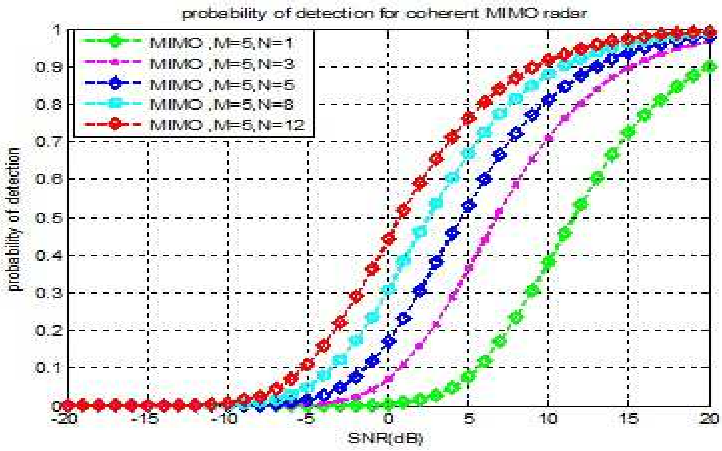

Fig. 3: Probability of detection for coherent MIMO radar, changing N.

If the number of transmit elements is held constant at the value of 5 and the number of receive elements is increased, the P_d vs SNR curve in Fig. 3 is obtained. We can see from the graph that as number of receiving antennas is increased the probability of detection increases, because the total received energy increases.

III. COHERENT MIMO RADAR WITH STC WAVEFORMS

In the detection problems studied so far for the coherent MIMO radar which employs antenna are close enough, are developed without including these space time coded (STC) signals explicitly. In the transmitted signals are modeled as a train of rectangular pulses n whose amplitudes are modulated by space time codes and the corresponding detectors are developed. With this approach, the transmitted signals can be further optimized to better a given performance metric. The STC Coherent MIMO radar configuration is shown in Fig. 4.

A. System Model

Consider a coherent MIMO radar with STC waveforms system that has transmit and a receive array consisting of M and N elements respectively. The received signal is also scaled so that the total received signal increases directly proportional to rectangular pulses. The resultant signal model for the received signal can be written as

$$y_k(t) = \sqrt{\frac{nE_t}{M}}\mathrm{H}x(t-\tau) + w_k(t) \dots\dots(7)$$

Where, $\sqrt{E_t/M}\,Hx(t-\tau)$ denote the discrete time baseband signal transmitted by the transmit antenna elements where $x(t-\tau)$ is the input message signal with delay time, E_t is the total average transmitted energy and $w_k(t)$ is the noise vector.

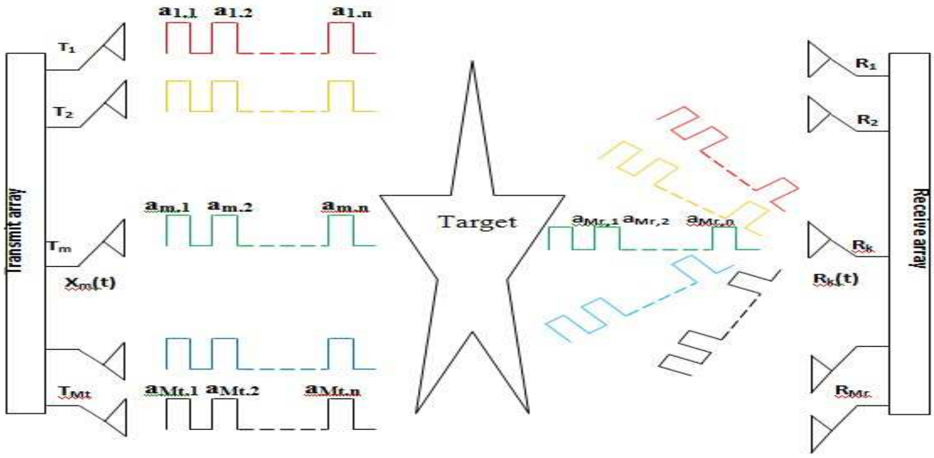

Fig.4. STC Coherent MIMO radar configuration.

B. Probability detection

The detection problem here can be formulated as binary hypothesis testing problem as follows:

$$\left.\begin{aligned} H_0&: y_k = w_k \\ H_1&: \; y_k = \sqrt{\frac{nE_t}{M}}\alpha_k + w_k \end{aligned}\right\} \dots\dots\dots (8)$$

Where H_0 indicates absence of signal and H_1 indicates presence of signal.

To see the performance limit of coherent MIMO radar, the vector α become identical and coherent integration of the received samples becomes possible before detection process and $\boldsymbol{w_k}$ is now a complex number.
For coherent MIMO radar with STC waveforms, from the definition of SNR for the radar system is

$$(SNR)_{STC} = \frac{nE_t}{\sigma_w^2} = n * SNR$$

Then P_d can be written in terms of SNR and probability of false alarm rate as,

$$P_d = exp\left(\frac{ln(P_{fa})}{(n * SNR)N + 1}\right) \dots\dots.(9)$$

C. Results and Observation

To compare with the detection performance of coherent MIMO radar with STC waveforms, the probability detection in equation (9) is implemented for which P_{fa} value is set to 10^{-2}. If the number of receiving elements is held constant at the value of 5, and the number of transmitting elements is increased, the P_d vs. SNR curve in Fig. 5 is obtained. The graphics in Fig. 5 show that the detection performance does not change with increasing M.

But if the number of transmitting elements is held constant at the value of 5, and the number of receiving elements is increased, the p_d vs. SNR curve in Fig. 6 is obtained. It is interesting to see that the detection performance increases as the number of receiving antennas increases.

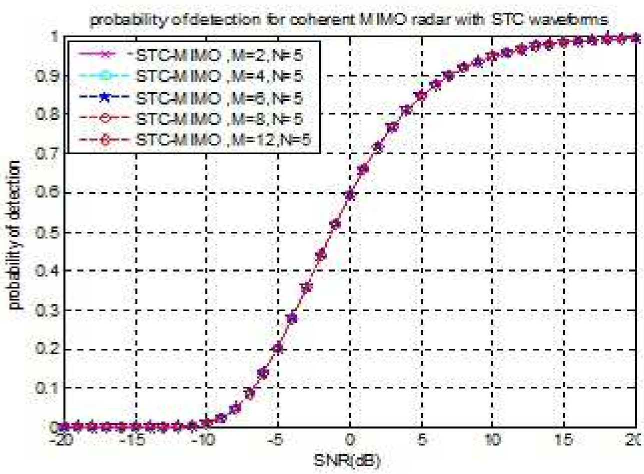

Fig. 5. Probability of detection for coherent MIMO radar with STC waveforms, changing M.

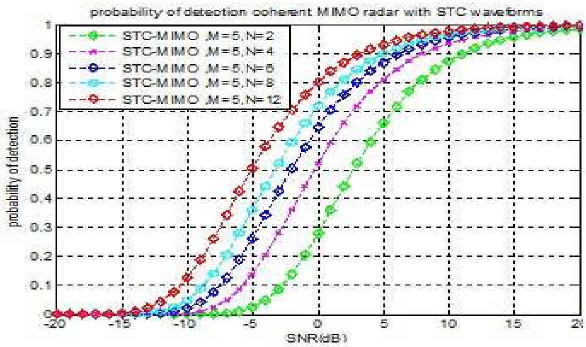

Fig. 6. Probability of detection for coherent MIMO radar with STC waveforms, changing N.

The ROC of coherent MIMO radar versus coherent MIMO radar with STC waveforms and also comparison of probability detection of both type of MIMO radar are is given in Fig. 7 and Fig. 8 respectively. These figures (Fig. 7 & Fig. 8) are obtained using the analytical expressions given in equations (6), (9) for $M = N = 5$. In the both figures, the blue lines belong to coherent MIMO radar with STC waveforms and the red lines belong to coherent MIMO radar.

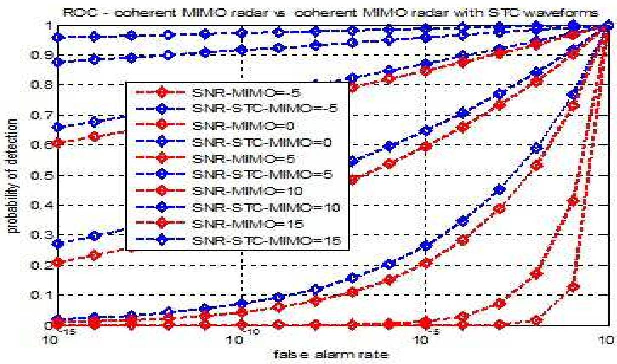

Fig. 7: ROC- Coherent MIMO vs. STC coherent MIMO radar.

The results in Fig.7 and 8 show that at high SNR values and at high detection probabilities, the detection performance of STC coherent MIMO radar is better than coherent MIMO radar.

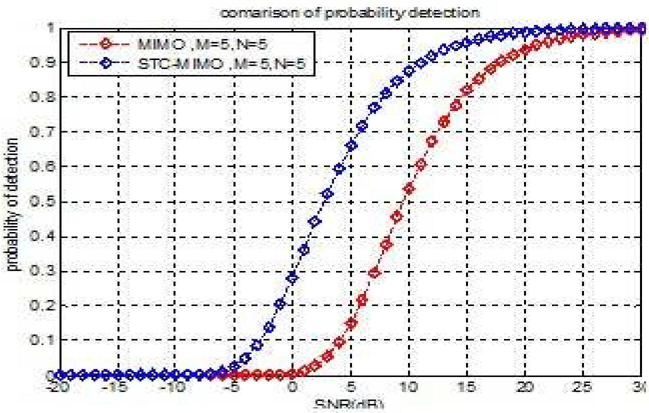

Fig. 8: Comparison of probability detection for coherent MIMO vs. STC coherent MIMO radar.

IV. CONCLUSION

In this paper, a wide variety of signal processing algorithms for coherent MIMO radar with and without STC waveforms have been presented. A novel algorithm on the space-time adaptive processing is proposed for improving the performance of coherent MIMO radar system. Derivations of the respective optimal detectors are shown when the target and noise level are either known or unknown. The coherent MIMO radar with pulse-train signalling outperforms the conventional MIMO radar at high detection rates which enables RCS fluctuation smoothing is demonstrated. The waveform design problem with information about the target and the clutter responses are being dealt. We have provided several numerical examples which show that the coherent MIMO radar with STC waveforms has much better performance than others. We also proposed a new metric to analyze the performance of these systems. Development of an adaptive optimal energy allocation mechanism is done to get significant improvement in performance. Finally we simulated a realistic scenario to analyze the performance of the proposed system. Using higher order modulations in MIMO systems with STC, we can achieve better detection rates, target localization and bandwidth efficiency.

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