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Signal Processing Algorithm of STC Waveforms for Statistical 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 widely spaced antennas. Multiple-input–multiple-output (MIMO) radar is an emerging technology that has significant potential for advancing the state-of-the-art of modern radar. This is a multiple antenna radar system capable of transmitting arbitrary waveform from each antenna element. Like MIMO communications, MIMO radar offers a new paradigm for signal processing research. It's significant potentials for fading mitigation, resolution enhancement, and interference and jamming suppression, which can result in significantly improved target detection, parameter estimation, target tracking and recognition performance. To identify a target in statistical MIMO radar system multiple antennas, not closely placed, for transmission and reception is used. This paper introduces the signal processing algorithm of STC in statistical MIMO radar for improved target detection and recognition performance. We consider the use of space–time coding (STC) to mitigate the waveform cross-correlation effects in MIMO radar. The optimal detector in the Neyman-Pearson sense is developed and analyzed for the statistical MIMO radar for with and without STC waveforms in case of stationary target. The performance improvement achieved by the use of STC waveforms in statistical MIMO radar is investigated. Finally, a number of numerical examples demonstrated for the effectiveness of the proposed approaches. Therefore, statistical MIMO radar can be applied to enhance radar resolution by allowing the measurement of one scatter at a time.

Index Terms*— *MIMO, Statistical, SNR, Probability detection, STC.

I. INTRODUCTION

Availing the benefit from the idea of MIMO communication systems, we explored the potentials of MIMO concept in radar [1]. MIMO radar can be defined simply as a multi-antenna radar system which transmits linearly independent or orthogonal waveforms. Our proposed MIMO radar enjoys similar benefits to those enjoyed by MIMO communication systems and targets provide a rich scattering environment. Conventional radars experience target fluctuations of 5-25 dB. Slow RCS fluctuations cause long fades in target RCS, degrading radar performance. The novelty of MIMO radar is that it provides measures to overcome those degradations or even utilizes the RCS fluctuations for new applications. Standard MIMO radar takes the opposite direction of the phased-array radar [3]. The approach is to employ multiple uncorrelated waveforms that are radiated via omnidirectional transmission, in compare to phased-array radar where a single probing waveform is sent via directional transmission. The MIMO systems have increased popularity for their ability to enhance all areas of system performance. MIMO radar may be configured with its antennas co-located or widely distributed over an area and are able to provide independent diversity paths. In particular, the term "statistical MIMO radar," refers to the signal model where the signals measured at different antennas are uncorrelated [3], [2]-[5]. If the antennas are separated far enough, the target RCS for different transmitting paths become independent random variables. Thus, each orthogonal waveform carries independent information about the target; and thus spatial diversity about the target is created. Exploiting the independence between signals at the array elements, MIMO radar achieves improved detection [6] performance and increased radar sensitivity. Full exploitation of these potentials can result in significant improvement in target detection, parameter estimation; target tracking and recognition performance [2].Thus comes the motivation for using MIMO radar. Thus, each orthogonal waveform carries independent information about the target; spatial diversity about the target. Exploiting the independence between signals at the array elements, MIMO radar achieves improved detection performance and increased radar sensitivity.

Space-Time Coding (STC) 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 Space-Time Coding '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 [7]. 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 capitalize upon parallel transmission paths within the propagation channel (for improved bandwidth efficiency). For more discussion of the scattering environment, and its influence on theoretical MIMO system capacity see [8].

In this paper, the signal processing algorithm of statistical MIMO radar [2] with STC waveforms is investigated. The similarities and differences of these radar systems from conventional radar systems are explored. The detectors for statistical MIMO radar with and without STC waveforms are provided and their detection performances are compared through numerical simulations. The optimal detector in the Neyman-Pearson sense is developed and analyzed for the statistical MIMO radar for both type of signal.

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The performance improvements achieved by statistical MIMO radar with STC waveforms system is better than statistical MIMO radar those are summarized.

II. STATISTICAL MIMO RADAR

Statistical MIMO radar employs antenna arrays which are widely separated. The inter element spacing in an array is also so large that each transmit-receive pair sees a different aspect of the target and thus sees different RCS due to target's complex shape. If the spacing between the antennas elements is wide enough, received signals from each transmit receive pair become independent. This is called spatial or angular diversity. Statistical MIMO radar focuses on this property.

A. System Model

The model of the statistical MIMO radar system is shown in Figure 1 where transmitters and receivers be widely separated.

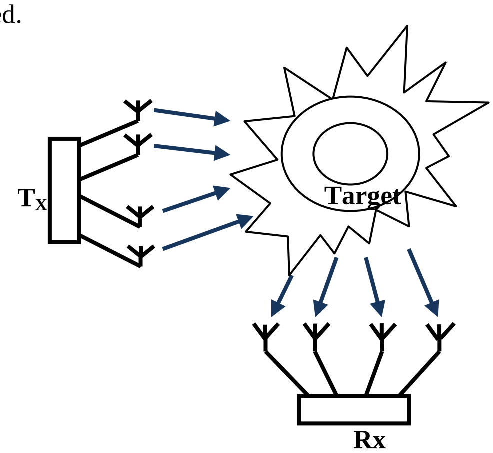

Figure 1. Statistical MIMO radar configuration.

If the received signal is fed to a bank of matched filters each of which is matched to $x_m(t)$, and the corresponding output is sampled at the time instant, then the output of the matched filter bank can be written in the vector form as

$$\bar{y} = \sqrt{\frac{E_t}{M}}\bar{\alpha} + \bar{w} \qquad \dots\dots\dots(1)$$

Where $\bar{y}$ is a $\mathrm{MN} \times 1$ complex vector whose entries correspond to the output of the each matched filter at every receiver, $\bar{\alpha}$ is a $\mathrm{MN} \times 1$ complex vector that contains all the elements of channel matrix (H) and $\bar{w}$ is a $\mathrm{MN} \times 1$ complex noise vector.

B. Probability detection

Statistical MIMO Radar can be formulated as binary hypothesis testing problem for H_0 indicates absence of signal and H_1 indicates presence of signal.

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

It is well known that the optimum solution to this hypothesis testing problem under Neyman-Pearson criterion is the Likelihood Ratio Test (LRT) as,

$$\frac{p(\bar{y}|H_1, C, A)}{p(\bar{y}|H_0, C)} \gtreqless_{H_0}^{H_1} T \dots\dots\dots\dots(3)$$

The P_{fa} can be calculated as in terms of threshold T',

$$P_{fa} = Prob\left\{\frac{\sigma_w^2}{2}\chi_{2MN}^2 > T'\right\}$$

$$= Prob\left\{\chi_{2MN}^2 > \frac{2}{\sigma_w^2}T'\right\}$$

$$= 1 - Q_{\chi_{2MN}^2} exp\left(\frac{2}{\sigma_w^2}T'\right) \dots\dots(4)$$

Where, $Q_{\chi_{2MN}^2}$ represents the cumulative distribution function of a Chi-squared random.

The P_d can be calculated in terms of P_{fa} and SNR as,

$$P_d = 1 - Q_{\chi_{2MN}^2}\left(\frac{1}{\left(\frac{SNR}{M} + 1\right)} Q_{\chi_{2MN}^2}^{-1}(1 - P_{fa})\right) \dots\dots.(5)$$

C. Results and Observation

To compare with the detection performance of statistical MIMO radar, the probability detection in equation (5) 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 Figure 2 is obtained.

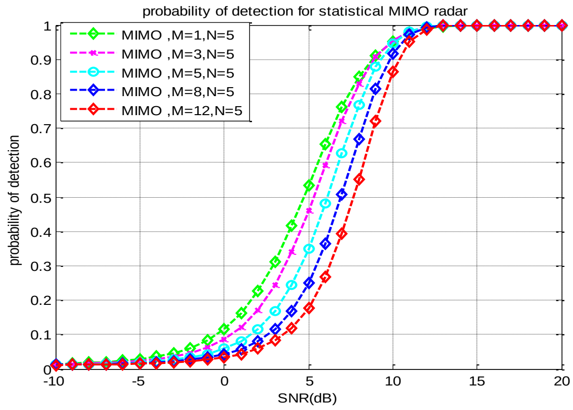

Figure 2. Probability of detection for statistical MIMO radar, changing M.

It is interesting to see that the detection performance decreases as the number of transmitting antennas increases. Because of this decrease in the detection performance; using more widely separated receiving antennas instead of increasing the number of spatially diverse transmitting antennas seems more reasonable.

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 Figure 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.

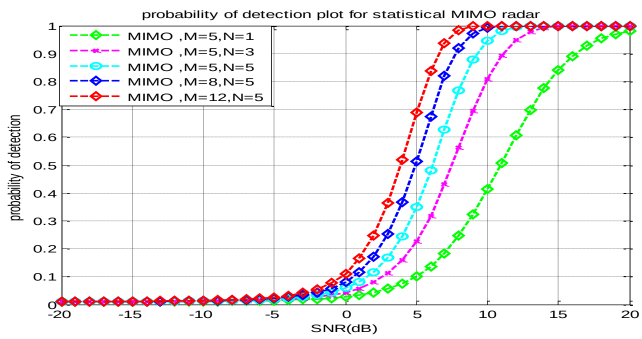

Figure 3. Probability of detection for statistical MIMO radar, changing N.

III. STATISTICAL MIMO RADAR WITH STC WAVEFORMS

In the detection problems studied so far for the statistical MIMO radar which employs antenna arrays which are widely separated, the transmitted signals are assumed to be orthogonal and the detectors are developed without including these space time coded (STC) signals explicitly. In the transmitted signals are modeled as a train of rectangular pulses 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 Figure 4.

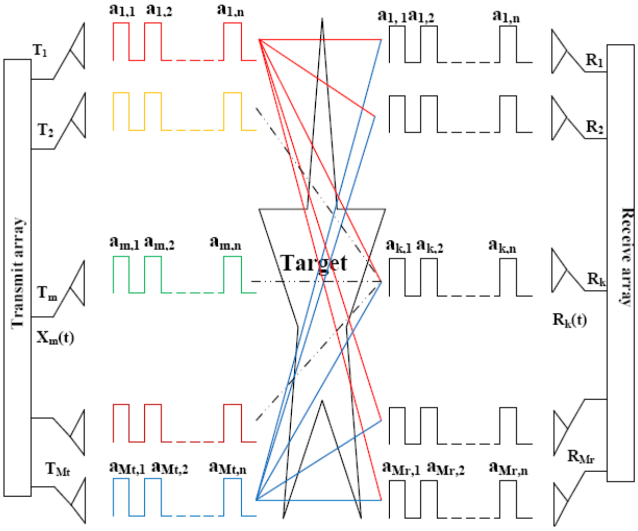

Figure 4. STC statistical MIMO radar configuration.

A. System Model

Consider a MIMO radar that has transmit array of M elements and a receive array of N elements. Assume each transmit antenna sends a coded pulse train of n pulses. The baseband equivalent of the transmitted signal by the mth transmit antenna can be written as

$$X_m(n) = \sum_{j=1}^{n} a_{m,j} p(t-(j-1)T_p) \quad \dots (6)$$

T_p represents pulse repetition period (PRI) and $a_{m,j}$ is a complex number which represents the code that modulates the j[th] pulse of the m[th] transmitting element in both amplitude and phase.

If the received signal is fed to a bank of matched filters each of which is matched to $X_m(n)$, and the corresponding output is sampled at the time instant, then the output of the matched filter bank can be written in the vector form as

$$y_k = \sqrt{NE_t} A a_k + w_k \quad \dots\dots(7)$$

B. Probability detection

The detection problem can be formulated as a binary hypothesis testing problem as:

$$\left.\begin{array}{ll} H_0: y_k = w_k & k = 1, \dots\dots, N \\ H_1: y_k = A a_k + w_k & k = 1, \dots\dots, N \end{array}\right\} \dots\dots\dots (8)$$

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

For statistical MIMO radar with STC waveforms, As a result the SNR definition of the radar system is

$$(SNR)_{STC} = \frac{nE_t}{\sigma_w^2} = n * SNR \quad \dots\dots (9)$$

The P_d can be calculated in terms of P_{fa} and $(SNR)_{STC}$ as,

$$P_d = 1 - Q_{\chi^2_{2MN}}\left(\frac{1}{\left(\frac{(SNR)_{STC}}{M}+1\right)} Q^{-1}_{\chi^2_{2MN}}(1-P_{fa})\right) \dots\dots (10)$$

$$P_d = 1 - Q_{\chi^2_{2MN}}\left(\frac{1}{\left(\frac{n * SNR}{M}+1\right)} Q^{-1}_{\chi^2_{2MN}}(1-P_{fa})\right) \dots\dots (11)$$

Where, $Q_{\chi^2_{2MN}}$ represents the cumulative distribution function of a Chi-squared random.

C. Results and Observation

To compare with the detection performance of statistical MIMO radar with STC waveforms, the probability detection in equation (11) 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 Figure 5 is obtained.

It is interesting to see that the detection performance is almost constant at the higher SNR as the number of transmitting antennas increases. 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 Figure 6 is obtained. It is interesting to see that the detection performance increases as the number of receiving antennas increases. Because of these increases in the detection performance; using more widely separated receiving antennas instead of increasing the number of spatially diverse transmitting antennas seems more reasonable.

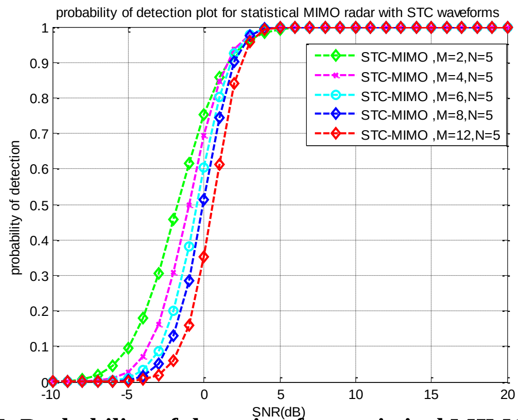

Figure 5. Probability of detection for statistical MIMO radar with STC waveforms, changing M.

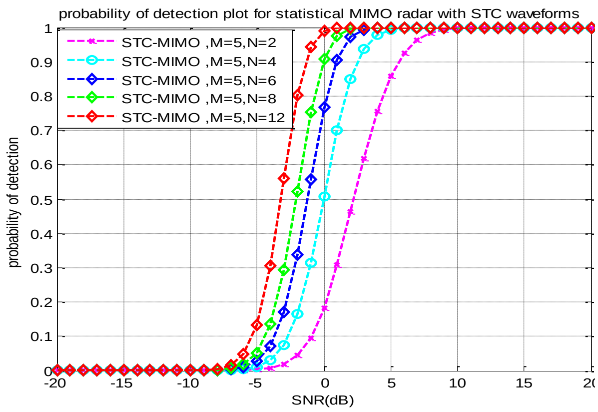

Figure 6. Probability of detection for statistical MIMO radar with STC waveforms, changing N.

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The ROC of statistical MIMO radar versus statistical MIMO radar with STC waveforms and also comparison of probability detection of both type of MIMO radar are is given in Figure 7 and Figure 8 respectively. These figures are obtained using the analytical expressions given in Equations (5), (11) for $M = N = 5$. In the both figures, the blue lines belong to statistical MIMO radar with STC waveforms and the red lines belong to statistical MIMO radar.

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

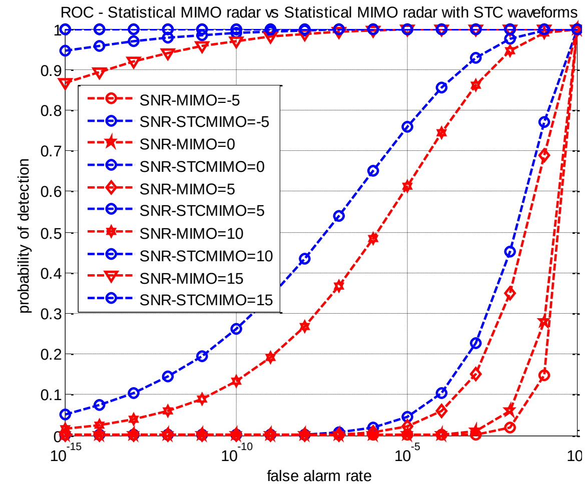

Figure 7: ROC- statistical MIMO vs. STC statistical MIMO radar.

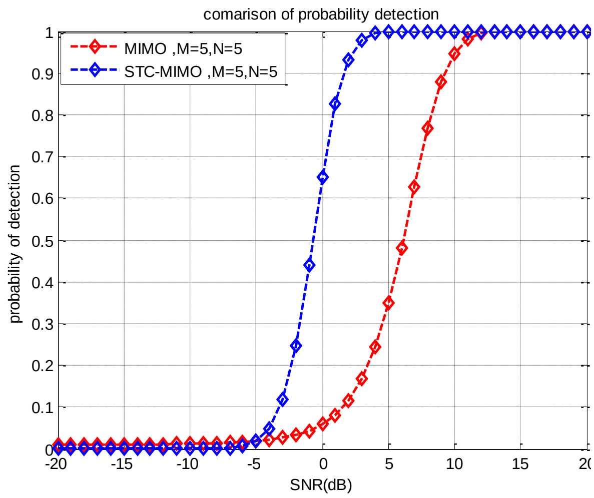

Figure 8: Comparison of probability detection for statistical MIMO vs. STC statistical MIMO radar.

IV. CONCLUSION

In this paper, a wide variety of signal processing algorithms for statistical 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 statistical MIMO radar system. Derivations of the respective optimal detectors are shown when the target and noise level are either known or unknown. The statistical 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 statistical MIMO radar with STC waveforms has much better performance. 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 Space Time Coding we can achieve better detection rates and bandwidth efficiency.

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