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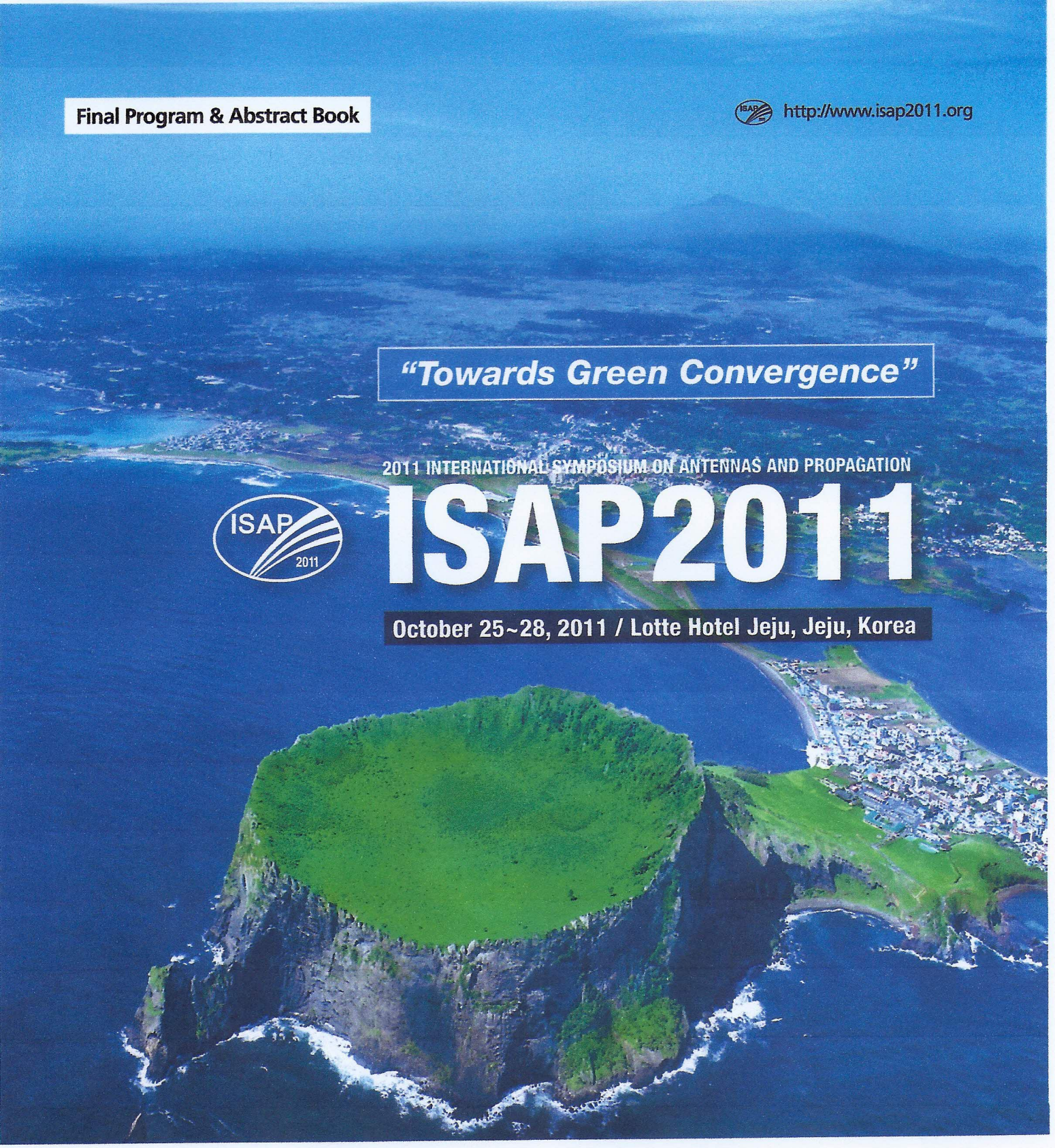

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Space-Time Coding in MIMO Radar Employing the Generalized Detector

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Abstract

We consider the problem of multiple-input multiple-output (MIMO) radars employing the generalized detector (GD) based on the generalized approach to signal processing in noise and using the space-time coding to achieve a desired diversity. To that end, we derive a suitable GD structure after briefly outlining the model of the received target return signal. The GD performance is expressed in closed form as a function of the clutter statistical properties and of the space-time code matrix.

Keywords : Generalized Detector Additive White Gaussian Noise Detection Performance Multiple-Input Multiple-Output Rayleigh Distribution

1. Introduction

Multiple-input multiple-output (MIMO) systems have received a great attention owing to the following viewpoints: a) MIMO systems have been deemed as efficient spatial multiplexers and b) MIMO systems have been deemed as a suitable strategy to ensure high-rate communications on wireless channels [1]. Space-time coding has been largely investigated as a viable means to achieve spatial diversity, and thus to contrast the effect of fading [2],[3]. We apply the generalized approach to signal processing (GASP) in noise [4],[5] to the design and implementation of MIMO radars used space-time coding technique. MIMO radar can be represented by m transmit antennas spaced several wavelengths apart and n receive antennas, whose purpose is to make the final decision as a "yes" target in the coverage area. If the spacing between the transmit antennas is large enough and so is the spacing between the receive antennas, a rich scattering environment is generated, and each receive antenna processes l statistically independent copies of a target echo. Unlike a conventional radar array system attempting to maximize the coherent processing, MIMO radar resorts to the diversity of target scattering in order to improve the detection performance. We use some key results from communication theory, and in particular, the well-known concept that, upon suitably space-time encoding the transmitted waveforms, a maximum diversity order given by $m \times n$ can be achieved. Import of these results in a radar scenario poses a number of problems, which form the object of the present study, and in particular: a) the issue of waveform design, which exploits the available knowledge as to space-time codes; b) issue of designing a suitable detection structure based on GASP, also in the light of the fact that the disturbance can no longer be considered as AWGN, due to the presence of clutter returns; and c) at the performance assessment level, the issue of evaluating the maximum diversity order that can be achieved and the space-time coding ensuring it under different instances of clutter and\or target. In the present paper, the first and third tasks are merged in the unified problem of determining the space-time coding achieving maximum diversity order in target detection, for constrained probability of false alarm, and for given clutter covariance. As to the second task, the decision-making criterion exploiting by GASP is employed.

2. System Model

We consider MIMO radar composed of m fixed transmitters and n fixed receivers and assume that the antennas as the two ends of the system are sufficiently spaced such that a possible target and/or clutter provides uncorrelated reflection coefficients between each transmit/receive pair of sensors. Denote by $s_i(t)$ the baseband equivalent of the coherent pulse train transmitted by i-th antenna

$$s_i(t) = \sum_{j=1}^{N} a_{i,j}\, p[t-(j-1)T_p], \qquad i = 1,\ldots,m \tag{1}$$

where $p(t)$ is the signature of each transmitted pulse, which we assume, without loss of generality, with unit energy and duration τ_p; T_p is the pulse repetition time;

$$\mathbf{a}_i = [a_{i,1},\ldots,a_{i,N}]^T , \tag{2}$$

is an N-dimensional column vector whose entries are complex numbers which modulate both in amplitude and in phase the N pulses of the train, where $(\cdot)^T$ denotes transpose. In the sequel, we refer to $\mathbf{a}_i$ as the code word of i-th antenna. The baseband equivalent of the signal received by i-th sensor, from a target with two-way time delay τ, can be presented in the following form

$$x_i(t) = \sum_{l=1}^{m} \alpha_{i,l} \sum_{j=1}^{N} a_{l,j}\, p[t-\tau-(j-1)T_p] + n_i(t) , \qquad i = 1,\ldots,n , \tag{3}$$

where $\alpha_{i,l}$, $i = 1,\ldots,n$ and $l = 1,\ldots,m$ are complex numbers accounting for both the target backscattering and the channel propagation effects between l-th transmitter and i-th receiver; $n_i(t)$, $i = 1,\ldots,n$, are zero-mean, spatially uncorrelated, complex Gaussian random processes accounting for both the external and the internal disturbance. For simplicity, we assume a zero-Doppler target, but all the derivations can be easily extended to account for a possible known Doppler shift. We explicitly point out that the validity of the above model requires the narrowband assumption

$$\frac{d_{\max}^m + d_{\max}^n}{c} << \frac{1}{B} , \tag{4}$$

where B is the bandwidth of the transmitted pulse, $d_{\max}^m$ and $d_{\max}^n$ denote the maximum spacing between two sensor at the transmitter and the receiver end, respectively. The signal $x_i(t)$, at each of the receive elements, is matched filtered to the pulse $p(t)$ by preliminary filter of the GD and the filter output is sampled at the time instants $\tau + (k-1)T_p$, $k = 1,\ldots,N$.

3. GD Design for MIMO Radar Systems

The problem of detecting a target with a MIMO radar system can be formulated as

$$\begin{cases} \mathcal{H}_0 \Rightarrow \ \mathbf{x}_i = \xi_{PF_i}, & i = 1,\ldots,n \\ \mathcal{H}_1 \Rightarrow \ \mathbf{x}_i = \mathbf{A}\boldsymbol{\alpha}_i + \xi_{PF_i}, & i = 1,\ldots,n \end{cases} \tag{5}$$

where ξ_{PF_i}, $i = 1,\ldots,n$ are statistically i.i.d. zero-mean complex Gaussian vectors with covariance

$$E[\xi_{PF_i}\xi_{PF_i}^*] = E[\xi_{AF_i}\xi_{AF_i}^*] = \mathbf{M} . \tag{6}$$

The covariance matrix (6) is assumed positive definite and known. According to the Neyman-Pearson criterion, the optimum solution to (5) must be the likelihood ratio test. However, it cannot be implemented since total ignorance of the parameters $\boldsymbol{\alpha}_i$ is assumed. One possible way to circumvent this drawback is to resort to the generalized likelihood ratio test (GLRT). Applying GASP to GLRT, we obtain the following decision rule

$$\frac{\max\limits_{\boldsymbol{\alpha}_1,\ldots,\boldsymbol{\alpha}_n} f(\mathbf{x}_1,\ldots,\mathbf{x}_n \mid \mathcal{H}_1, \mathbf{M}, \boldsymbol{\alpha}_1,\ldots,\boldsymbol{\alpha}_n)}{f(\xi_{AF_1},\ldots,\xi_{AF_n} \mid \mathcal{H}_0, \mathbf{M})} \underset{<_{\mathcal{H}_0}}{>^{\mathcal{H}_1}} K_g , \tag{7}$$

$f(\mathbf{x}_1,\ldots,\mathbf{x}_n \mid \mathcal{H}_1, \mathbf{M}, \boldsymbol{\alpha}_1,\ldots,\boldsymbol{\alpha}_n)$ is the pdf of the data under the hypothesis $\mathcal{H}_1$ and $f(\xi_{AF_1},\ldots,\xi_{AF_n} \mid \mathcal{H}_0, \mathbf{M})$ is pdf at the hypothesis $\mathcal{H}_0$, respectively, K_g is a suitable modification of the original threshold. Previous assumptions imply that the aforementioned pdfs can be written in the following form:

$$f(\xi_{AF_1},\ldots,\xi_{AF_n} \mid \mathcal{H}_0, \mathbf{M}) = \frac{1}{\pi^{Nn}\det^n(\mathbf{M})} \exp\left[-\sum_{i=1}^{n} \xi_{AF_i}^* \mathbf{M}^{-1} \xi_{AF_i} \right] \Rightarrow \mathcal{H}_0 , \tag{8}$$

$$f(\mathbf{x}_1,\ldots,\mathbf{x}_n \mid \mathcal{H}_1, \mathbf{M}, \boldsymbol{\alpha}_1,\ldots,\boldsymbol{\alpha}_n) = \frac{1}{\pi^{Nn}\det^n(\mathbf{M})} \exp\left[-\sum_{i=1}^{n} (\mathbf{x}_i - \mathbf{A}\boldsymbol{\alpha}_i)^* \mathbf{M}^{-1} (\mathbf{x}_i - \mathbf{A}\boldsymbol{\alpha}_i) \right] \Rightarrow \mathcal{H}_1 . \tag{9}$$

Substituting (8) and (9) in (7), we can recast the GLRT based on GASP in the following form

$$\sum_{i=1}^{n}\xi_{AF_i}^{*}\mathbf{M}^{-1}\xi_{AF_i}-\sum_{i=1}^{n}\min_{\boldsymbol{\alpha}_i}(\mathbf{x}_i-\mathbf{A}\boldsymbol{\alpha}_i)^{*}\mathbf{M}^{-1}(\mathbf{x}_i-\mathbf{A}\boldsymbol{\alpha}_i)\underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\gtrless}}K_g \quad . \tag{10}$$

4. Performance Analysis

To define possible design criteria for the space-time coding, we must establish a direct relationship between the detection performance and the transmitted waveform. At the hypothesis $\mathcal{H}_0$, the GLRT based on GASP is the GD background noise

$$\sum_{i=1}^{n}\xi_{AF_i}^{*}\mathbf{M}^{-1}\xi_{AF_i}-\sum_{i=1}^{n}\xi_{PF_i}^{*}\mathbf{M}^{-1}\xi_{PF_i} \quad . \tag{11}$$

The decision statistic is defined by McDonald's function with $m\times n$ degrees of freedom. The P_{FA} can be evaluated in the following form

$$P_{FA}=\exp(-K_g)\sum_{k=0}^{n}\frac{(K_g)^k}{k!} \quad . \tag{12}$$

We see that: a) the decision statistic is ancillary but its pdf is functionally independent of such a matrix; b) the threshold setting is feasible with no prior knowledge as to the clutter power spectrum GLRT based on GASP ensures CFAR property. At $\mathcal{H}_1$, given $\boldsymbol{\alpha}_i$, the vectors $\mathbf{x}_i$, $i=1,\ldots,n$, are statistically independent complex Gaussian vectors with the mean $\mathbf{M}^{-1}\mathbf{A}\boldsymbol{\alpha}_i$ and identity covariance matrix It follows that, given $\boldsymbol{\alpha}_i$, the GLRT based on GASP is no the central distributed modified second-order Bessel function of an imaginary argument, with the no centrality parameter $\sum_{i=1}^{n}\boldsymbol{\alpha}_i^{*}\mathbf{A}^{*}\mathbf{M}^{-1}\mathbf{A}\boldsymbol{\alpha}_i$ and degrees of freedom $m\times n$. The conditional P_D can be presented in the following form

$$P_D=Q_{m\times n}\left(\sqrt{2q},\sqrt{2K_g}\right) \text{ , where } \quad q=\sum_{i=1}^{n}\boldsymbol{\alpha}_i^{*}\mathbf{A}^{*}\mathbf{M}^{-1}\mathbf{A}\boldsymbol{\alpha}_i \tag{13}$$

$Q_k(\cdot,\cdot)$ is a generalized Marcum Q-function of order k. Alternative expression for the conditional P_D

$$P_D=\sum_{k=0}^{\infty}\frac{\exp(-q)q^k}{k!}\left[1-\Gamma_{inc}(K_g,k+m\times n)\right] \text{ , where } \quad \Gamma_{inc}(p,r)=\frac{1}{\Gamma(r)}\int_0^w\exp(-z)z^{r-1}dz \tag{14}$$

is the incomplete Gamma function.

5. Simulation

We assume uncorrelated disturbance, whereby orthogonal space-time codes are optimal. In this scenario, simulations have been run and the results have been compared to the Chernoff bounds of the conventional GLRT receiver and to GD performance through SISO radar system. Effect of the disturbance correlation is considered, and the impact of an optimal code choice is studied under different values of transmit/receiver antenna numbers. Figure 1 represents AWG disturbance. We consider the optimum coded radar system and the encoded one. P_D is plotted versus SCR at $P_{FA}=10^{-4}$ and $N=m=n=2$. This simulation setup implies that the Alamouti code is optimum. For comparison we plot the performance of encoded SISO GD. We presented the performance of conventional GLRT to underline a superiority of GD. Superiority of employment GD with respect to the conventional GLRT radar systems achieves 6 dB for the optimum coding, 8 dB for the encoding, and 12 dB for SISO radar systems. The effect of number n of receive antennas on the performance is analyzed in Fig.2. Superiority of GLRT GD radar systems over conventional GLRT is evident and estimated at the level of 6 dB at $n=8$ and 10 dB in the case of a MISO (i.e., $n=1$) for $P_D=0.9$. Notice that this performance trend is also in accordance with the expression of the mutual information that exhibits a linear, monotonically increasing, dependence on n. The same qualitative, but not quantitative, performance can be presented under study of the number m of available transmit antennas on the GLRT GD radar system performance.

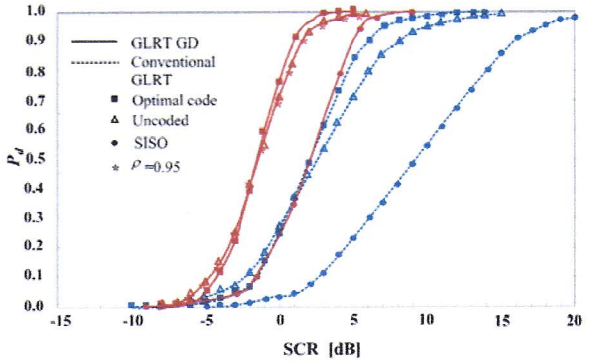

Figure 1: P_D versus SCR; white Gaussian disturbance and disturbance with exponentially shaped covariance matrix ($\rho = 0.95$).

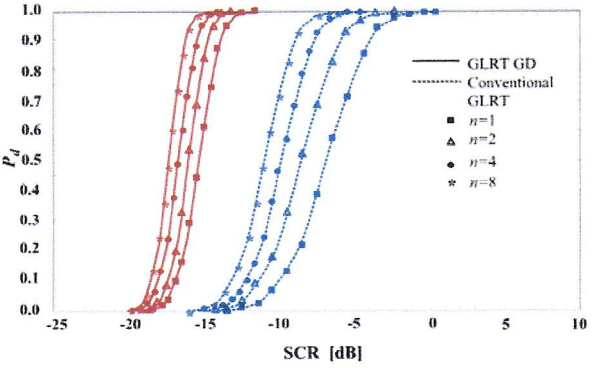

Figure 2: P_D of optimum coded system versus SCR; disturbance with exponentially shaped covariance matrix ($\rho = 0.95$).

5. Conclusions

The performance assessment that has been undertaken under several instances of number of receive-transmit antennas, and of clutter covariance, has confirmed that MIMO GD radar systems with a suitable space-time coding achieve significant performance gains over SIMO, MISO, SISO, or conventional SISO radar systems employing the conventional GLRT detector. Also, these MIMO GD radar systems outperform the listed above systems employing the conventional GD. Future research might concern the extension of the proposed framework to the case of an unknown clutter covariance matrix, in order to come up with a fully adaptive detection system.

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