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Adaptive polarimetric detection method for target in partially homogeneous background

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ABSTRACT

In this paper, the problem of enhancing the detection performance of detector for target in partially homogeneous background is addressed. Based on a general measurement model, a new constant false alarm rate (CFAR) adaptive matched detector (AMD) is proposed through a two-step design procedure. The detection performance of the AMD is theoretically analyzed. Then, the correctness of the analytical results and the effectiveness of the AMD are validated through numerical experiments and IPIX radar data. To further improve the detection performance of AMD, optimal polarimetric waveform design is approached. The waveform is designed by optimally selecting the transmitted polarization that maximizes a non-central parameter of the detection probability. Numerical experiments are provided to validate the performance improvement by comparing the optimal AMD with the optimal adaptive subspace detector (ASD) and the fixed AMDs. Comparison results show that a gain of 1–5 dB is obtained by the optimal AMD.

1. Introduction

The problem of detecting target in noisy background is a very common one in radar, sonar and navigation fields. Researches on this problem first emphasized on homogeneous background, in which noise in primary data is assumed to be independent identically distributed with that in secondary data. In this background, the generalized likelihood ratio detector (GLRD) [1] and adaptive matched filter (AMF) [2] are two classical detectors. The GRLD designs the test statistic by replacing the unknown parameters, i.e., the signal and the noise covariance matrix (NCM), with their maximum likelihood estimations (MLEs). Differently, the AMF designs the test statistic by first assuming that noise is known a prior and then replaces the NCM with its MLE. They are usually referred to as one-step and two-step detectors, respectively [3,4].

In many real scenarios, however, noise in primary data is not the same as that in secondary data. For example, in an airborne radar system, the noise in primary data and secondary data is generated from different reflection grounds which cause the noise power in test cell that differs from that in adjacent cells [5]. Another example for this background is in wireless communication systems; the signal of interest in different cells is faded by multiple sources of interference and multipath effect [6]. In this background, noise in primary data is assumed to have the same covariance structure with different power, which is also referred to as partially homogeneous background. Many detectors, such as matched subspace detector (MSD) [7–9] and adaptive subspace detectors (ASDs) [4,10–12], are proposed to deal with the target detection problem in partially homogeneous background. Besides, many detectors, such as texture-free GLR test (TF-GLRT) [13] and threshold-system-based detector (TD) is defined and used in [14], are proposed

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for target detection in other non-homogeneous background, e.g., compound-Gaussian background. Lombardo et al. [13] and Guo et al. [14] treat the scaling factor (referred to as the texture) as a random variable. The scaling factor appears in both null hypothesis and alternative hypothesis.

When target is static or slowly moving, the detection is a challenging problem in heavy noise background since discriminating a target using the Doppler effect is not possible. Polarization diversity has been proved to provide additional information to improve detection performance [15–19]. With the aid of polarization information, the GLRD and the AMF are extended to the polarization-space–time GLRD (PST-GLRD) [20] and the polarimetric AMF (PAMF) [19] for homogeneous background, respectively. Performance improvements of the MSD and the ASD with polarization information are discussed in [22,23] for partially homogeneous background.

The two-step AMF/PAMF has simpler form than that of the one-step GLRD/PGLRD in homogeneous background. To our knowledge, detectors for target in partially homogeneous background, such as the ASD, are designed with one-step procedure. Inspired by the two-step procedure in AMF/PAMF, a two-step design procedure is adopted to design detector for target detection in partially homogeneous background in this paper.

The proposed detector is expected to have a simpler form than the one-step ASD. Let α be a scaling factor representing the power difference of the noise in primary data and secondary data. The test statistic is designed under an assumption that the scaling factor α and the covariance matrix $\mathbf{R}$ are known a prior. Then α and $\mathbf{R}$ are replaced by their MLEs. To distinguish the proposed detector from the two-step AMF in homogeneous background, the proposed detector is referred to as an adaptive matched detector (AMD). The detection performance of the AMD is theoretically analyzed. The advantage of the AMD over the ASD and the TF-GLRT is validated with numerical simulations and IPIX radar data.

To further improve the detection performance of the AMD, optimal polarimetric waveform design is approached. Based on the analytical detection probability, the general solution to maximize the detection probability is to maximize the non-central parameter. Hence, the optimal AMD with polarimetric waveform design strategy is to optimally select the transmitted polarization that maximizes the non-central parameter. After obtaining the polarimetric data with the aid of vector sensor arrays [24], the detection performance improvement is validated.

The remainder of the paper is organized as follows. In Section 2, a measurement model including target and noise is described. The AMD is proposed and its detection performance is theoretically analyzed in Section 3. Polarimetric waveform design for the AMD is proposed and its effectiveness is validated in Section 4. In Section 5, the advantages of the AMD and its polarimetric waveform design are discussed. Conclusions are drawn in the final section.

2. Problem formulation

Secondary data is assumed to be known a prior. Let K, N and r represent the secondary data size, the system dimension and the signal dimension, respectively. Measurement model including target can be expressed as

$$\vec{y} = \mathbf{A}\vec{x} + \vec{n}, \tag{1}$$

where $\vec{y}$ is an $N \times 1$ dimensional complex measurement vector. $\mathbf{A}$ is an $N \times r$ system response matrix (SRM) which carries the information of the transmitted waveform and the receiver sensor array. $\vec{x}$ is an $r \times 1$ dimensional complex target vector and $\vec{n}$ is an $N \times 1$ complex noise vector. The SRM is such that $N > r$ and $\mathrm{rank}(\mathbf{A}) = r$ to ensure that the non-singularity of the estimated NCM [18,25].

In non-homogeneous background, taking compound-Gaussian background for instance, noise is distributed as $\sqrt{\kappa}\vec{g}$. The texture κ has the generalized Gamma probability density function (PDF) and $\vec{g}$ is a Gaussian distribution with zero mean and covariance matrix $\mathbf{R}$ [13]. Let $\mathbf{R}_1$ and $\mathbf{R}_2$ represent the NCMs in test cell and adjacent cell, respectively. Measurement with only the noise in these two cells can be written as

$$\begin{cases} \vec{y} = \vec{n} \sim CN(0, \mathbf{R}_1) \\ \vec{y}_k = \vec{n}_k \sim CN(0, \mathbf{R}_2). \end{cases} \tag{2}$$

Partially homogeneous background assumes that the noise in primary data has the same covariance structure as that in secondary data but with different power. It is an important and common scenario for target detection in non-homogeneous background. Lots of notable research works about this background have been studied [5–12,26–29]. This paper focuses on the discussion of target detection in partially homogeneous background. Let α be a scaling factor describing the power difference of the noise in primary data and secondary data. Hence, we have $\mathbf{R}_1 = \alpha\mathbf{R}$ and $\mathbf{R}_2 = \mathbf{R}$. Then, the noise in primary data and secondary data is distributed according to $CN(0, \alpha\mathbf{R})$ and $CN(0, \mathbf{R})$, respectively. The target detection problem is a composite hypothesis test which includes the null hypothesis H_0 and alternative hypothesis H_1:

$$\begin{cases} \mathrm{H}_0: & \begin{cases} \vec{y} = \vec{n}_k \sim CN(0, \alpha\mathbf{R}) \\ \vec{y}_k = \vec{n}_k \sim CN(0, \mathbf{R}), \quad k = 1, \ldots, K, \end{cases} \\ \mathrm{H}_1: & \begin{cases} \vec{y} = \mathbf{A}\vec{x} + \vec{n} \sim CN(\mathbf{A}\vec{x}, \alpha\mathbf{R}) \\ \vec{y}_k = \vec{n}_k \sim CN(0, \mathbf{R}), \quad k = 1, \ldots, K, \end{cases} \end{cases} \tag{3}$$

where $\vec{y}$ and $\vec{y}_k$ $(k = 1, 2, \ldots, K)$ represent the measurements from primary data and secondary data, respectively. Note that the scaling factor α accounts for the noise power mismatch between primary data and secondary data. When $\alpha = 1$, it represents a homogeneous background in which the noise is statistically the same in different cells. However, in partially homogeneous background, the noise power in primary data is not equal to that in secondary data; hence, α in this background is not always equal to 1.

3. Adaptive matched detector for detecting target in partially homogeneous background

In this section, the AMD for detecting target in partially homogeneous background is proposed. It is resorted to an ad hoc two-step procedure based on the generalized