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Design of MIMO radar waveform covariance matrix for Clutter and Jamming suppression based on space time adaptive processing

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ABSTRACT

This paper studies the optimization of waveform covariance matrix (WCM) for airborne multiple-input-multiple-output (MIMO) radar systems in the presence of clutter and jamming. The goal is to enhance the target detection performance by suppressing the clutter and jamming based on space time adaptive processing (STAP). We employ the signal-to-interference-plus-noise ratio (SINR) as the figure of merit. Assuming a known target steering vector, we recast the WCM design problem into a convex optimization problem. Through a max-min approach, we also make the designed WCM robust to the target steering vector, i.e., we develop a method to design WCM that maximizes the worst-case SINR associated with an uncertainty set. We explicitly derive the target steering vector corresponding to the worst-case SINR and solve the robust design of WCM via convex optimization. Finally, we provide several numerical examples to demonstrate the superiority of the proposed algorithms over the existing methods.

1. Introduction

Multiple-input-multiple-output (MIMO) radar is an emerging technology which has attracted considerable interests in recent years (see, e.g., [1–4] and the references therein). Different from traditional phased-array radar, MIMO radar system has the capability of transmitting multiple independent waveforms simultaneously. Currently, two typical configurations of MIMO radar have been proposed. The first type is called statistical MIMO radar (i.e., MIMO radar with widely separated antennas) [3]. By exploiting spatial diversity, statistical MIMO radar can improve the target detection performance and localization accuracy [3,4]. The colocated MIMO radar is the second type providing better parameter identifiability and clutter suppression capabilities [1,5,2]. For both types of MIMO radar, we can obtain additional performance enhancement through transmitting suitable designed waveforms. Therefore, waveform optimization for MIMO radar has received significant attention (see, e.g., [6–17] and the references therein). In particular, the optimized waveform covariance matrix (WCM, or signal cross-correlation matrix) has been shown to play a central role in enhancing the performance of MIMO radar. In [6,7], the authors showed that MIMO radar could synthesize a desired transmit beampattern flexibly through the design of WCM. Considering that the steering vectors are subject to uncertainties in practice, the authors of [18,19] proposed robust designs of the WCM that had improved transmit beampattern. In [9], the authors demonstrated that the radar system could achieve better parameter estimation

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accuracy (or lower the Cramér-Rao bound, equivalently) by designing WCM. In [8], it was shown if the WCM shared the same eigenvectors as those of the target covariance matrix, the WCM maximized the mutual information between the received signal and target scattering matrix as well as minimized the minimum mean square error (MMSE) of target parameter estimation. In [20,21], the authors designed the WCM to optimize the mutual information and the lower Chernoff bound, showing significant enhancement of the target detection performance.

Detecting ground-moving targets is one important application of MIMO radar systems. Typically, such a radar system is mounted on an airborne platform. Due to the nonzero relative motion between the radar system and ground, the clutter spectrum is spread over the whole Doppler frequency and the system detection performance is limited by the strong clutter and (possible) intentional jamming. Therefore, we have to suppress the clutter and jamming simultaneously to improve the detection performance. As a well-established technique in radar society, space time adaptive processing (STAP), which refers to the processing of signals from multiple antennas and multiple pulses, has the capability of jamming mitigation and clutter cancellation (see, e.g., [22,23]). In addition, recent studies have shown that, compared with conventional single-input-multiple-output (SIMO) STAP systems, MIMO-STAP systems (i.e., MIMO radar systems with STAP) have much sharper clutter notches and improved minimum detectable velocity (MDV) performance [1,24–26]. Other benefits of a MIMO-STAP system include lower probability of intercept (LPI), increased Doppler resolution, reduced clutter level and related hardware requirement, etc.

In this paper, we focus on the WCM design problem for MIMO-STAP systems to enhance the weak-target detection performance. In [27], the authors have discussed the waveform optimization problem under a MIMO-STAP architecture. Therein, they used the output signal-to-interference-plus-noise ratio (SINR, here interference means clutter and possible jamming) as the criterion. They proposed diagonal loading of the clutter covariance matrix to formulate the waveform design problem as a convex optimization problem. However, the loading factor was chosen in a rather *ad hoc* way and its selection remained unsolved. In addition, the solution associated with the diagonal loading approach is suboptimal.

Considering the target steering vector uncertainty, the authors in [28] studied the robust waveform design of MIMO STAP. By resorting to a max–min approach, they attempted to design waveforms which could maximize the worst-case SINR (over an uncertainty set of target steering vectors). However, the relaxed constraint (on the target steering vector) and the diagonal loading of the WCM also make the designed waveforms suboptimal.

This paper employs the same signal model as that in [27] and [28], and proposes new algorithms to design WCM for MIMO-STAP systems. For the case where the target steering vector is exactly known, we obtain the optimal WCM without diagonal loading and the performance associated with the designed WCM is superior to that in [27]. For the case of uncertain target steering vectors, we derive the “worst” steering vector that leads to the smallest SINR (over the uncertainty set of target steering vectors) and reformulate the waveform design based on the maximization of worst-case SINR into a convex optimization problem. The proposed algorithm avoids the problem of loading factor selection and enjoys better performance.

The rest of paper is organized as follows. We present the signal model in Section 2. We solve the WCM design with exactly known target steering vectors in Section 3. In Section 4, we solve the robust WCM design for the case of uncertain target steering vectors. We provide several numerical examples in Section 5 to demonstrate the performance of the proposed algorithm. Finally, we conclude the paper in Section 6.

Notations: Throughout this paper, matrices are denoted by bold capital letters, and vectors are denoted by bold lowercase letters. Superscript $(\cdot)^T$, $(\cdot)^*$ and $(\cdot)^H$ denote transpose, complex conjugate and conjugate transpose, respectively. vec($\mathbf{X}$) indicates the vector which is obtained by column-wise stacking of the matrix $\mathbf{X}$. tr$(\cdot)$ indicates the trace of a square matrix. $\mathbb{C}$ denotes the set of complex numbers, and $\mathbb{C}^{m\times n}$ are the sets of matrices of size $m\times n$ with entries from $\mathbb{C}$. $\mathbf{I}_M$ denotes an identity matrix of size $M\times M$. For $\mathbf{A}\in\mathbb{C}^{m\times m}$, $\mathbf{A}\succcurlyeq(\succ)\mathbf{0}$ indicates $\mathbf{A}$ is positive semidefinite (definite). The symbols $\otimes$ and $\odot$ denote Kronecker and Hadamard product, respectively. Finally, $\mathbb{E}(\mathbf{x})$ denotes the expectation of a random variable $\mathbf{x}$.

2. Signal model

Consider an airborne colocated MIMO radar with N_{T} transmit antennas and N_{R} receive antennas, as illustrated in Fig. 1. Assume for simplicity both of the transmit and receive arrays are equispaced, with inter-element spacings d_{T} and d_{R}, respectively. Then the signal reaching the ground moving target can be represented by [29,30]

$$\mathbf{a}^T(\theta_{\mathrm{t}})\mathbf{S}, \tag{1}$$

where $\mathbf{a}(\theta_{\mathrm{t}})=[1, e^{j2\pi f_{t,s}},\ldots,e^{j2\pi f_{t,s}\times(N_{\mathrm{T}}-1)}]^T$ denotes the transmit array steering vector of the target, $f_{t,s}=d_{\mathrm{T}}\sin\theta_{\mathrm{t}}/\lambda$ is the target spatial frequency, λ is the wavelength, θ_{t} is the target cone angle which satisfies $\sin\theta_{\mathrm{t}}=\cos\theta_{\mathrm{t}}^{\mathrm{EL}}\sin\phi_{\mathrm{t}}$, $\theta_{\mathrm{t}}^{\mathrm{EL}}$ and ϕ_{t} are the elevation and azimuth of the target,

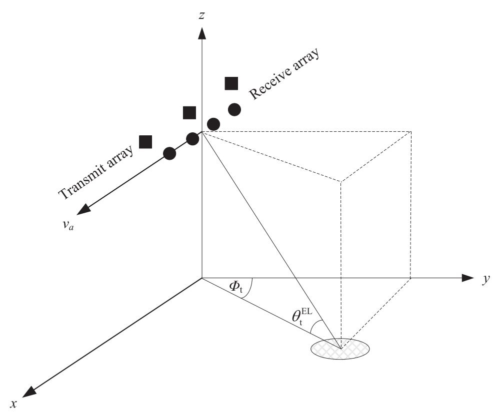

Fig. 1. Illustration of system layout.