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Fast communication

Conjugate ESPRIT for DOA estimation in monostatic MIMO radar ☆

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ABSTRACT

In this paper, a novel conjugate ESPRIT (C-ESPRIT) method for direction of arrival (DOA) estimation in monostatic MIMO radar is proposed. Firstly, a reduced-dimensional matrix is employed to transform the data matrix into a low dimensional space. Then the properties of noncircular signals are utilized to construct a new virtual array, whose elements are twice that of the monostatic MIMO radar virtual array with distinct elements. The rotational invariance properties of the new virtual array are figured out to estimate DOA through ESPRIT. Compared with the reduced-dimensional ESPRIT (RD-ESPRIT), the proposed method improves the angular estimation accuracy significantly and detects more targets. Simulation results verify the effectiveness of the proposed method.

1. Introduction

Multiple-input multiple-output (MIMO) radar [1], which is developed based on MIMO communication theory, has been widely investigated in recent years, owing to a lot of potential advantages over the conventional phased-array radar, such as more degree of freedom (DOF) [2], better parameter identifiability [2], higher angular estimation accuracy [3] and so on. At the transmit side, MIMO radar uses multiple antennas to emit simultaneously several independent waveforms instead of coherent waveforms. At the receive side, MIMO radar uses multiple antennas to receive echo signals which are matched by the whole transmitted waveforms. In general, according to the configuration of transmit and receive antennas, MIMO radar can be grouped into two classes. One class is named as statistical MIMO radar [3,4], whose transmit antennas and receive antennas are widely spaced. The other is named as colocated MIMO radar [5–13], including bistatic and monostatic MIMO radar, whose transmit antennas and receive antennas are closed spaced. The former can obtain coherent processing gain for solving target scintillation problem. The latter aims at obtaining virtual aperture which is larger than real aperture, so it brings narrower beamwidth and lower sidelobes and provides higher angular resolution and angular estimation accuracy.

Estimation direction of arrival (DOA) of multiple targets from the received signals corrupted by noise is one of the most important aspects in array signal processing [6] and MIMO radar [2]. In MIMO radar, a variety of methods have been proposed [7–14]. In [7], a two-dimensional Capon method is applied to estimate the direction of arrival (DOA) and direction of departure (DOD), but it needs two-dimensional spatial spectrum peak searching with high computation cost. In order to alleviate the heavy computational burden, a reduced-dimensional Capon (RD-Capon) algorithm [8] is presented to DOD and DOA estimation, which only needs one-dimensional spatial spectrum peak searching, and the angle estimation performance is close to the two-dimensional spatial spectrum peak searching method. In [9], an ESPRIT algorithm is proposed which exploits the rotational invariance property of both the transmit and receive arrays and does not need spectral peak searching. Whereas it requires the additional pairing procedure. The relationship between the two one-dimensional ESPRIT is investigated in [10]

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and the DOD and DOA are automatically paired. In [11], the polynomial root finding technique for joint DOD and DOA estimation without pairing is presented. In [12], an angle estimation algorithm which utilizes ESPRIT and SVD of cross-correlation matrix of the received data from two transmit subarrays is proposed. It provides good angle estimation performance even under the spatial noise environment. In [13], a reduced-dimensional ESPRIT (RD-ESPRIT) algorithm is developed for DOA estimation in monostatic MIMO radar, and the angular estimation accuracy is only improved slightly. A transmit beamspace energy focusing technique for DOA estimation is presented in [14], and the SNR gain at each receive antenna is maximized. It provides better angle estimation performance than conventional methods. However, the number of estimated target is limited. In [15], the potential advantages of noncircular signal such as binary phase shift keying (BPSK) and M-ary amplitude shift keying (MASK) applied in radar system are described, which includes: improving DOA estimation, radar detection and anti-jamming, etc.

In this paper, the monostatic MIMO radar with the noncircular signals is considered and a novel conjugate ESPRIT method for DOA estimation is proposed. Owing to the fact that the transmit–receive steering vector of the monostatic MIMO radar has only $2M-1$ distinct elements, a $M^2 \times (2M-1)$ reduced-dimensional matrix is designed to convert the transmit–receive steering vector with the size $M^2 \times 1$ into the virtual uniform linear array vector with the size $(2M-1) \times 1$, where M is the number of array elements. Then a new virtual array is constructed by using the properties of noncircular signals, whose elements are twice as many as the monostatic MIMO radar virtual array with distinct elements. Thus, the maximum number of identified targets for the new virtual array with $4M-2$ distinct elements can be $4M-4$. Finally, the rotational invariance properties of the new virtual are found out, and the DOA can be estimated by ESPRIT. Simulation results show that the proposed method provides better angle estimation performance than other methods.

The rest of the paper is organized as follows. The monostatic MIMO radar signal model is presented in Section 2. The proposed conjugate ESPRIT for DOA estimation is proposed in Section 3. In Section 4, simulation results are provided to verify the performance of the proposed algorithm. Finally, Section 5 concludes this paper.

Notation: $(\cdot)^H$, $(\cdot)^T$, $(\cdot)^{-1}$ and $(\cdot)^*$ denote the Hermitian transpose, transpose, inverse, complex conjugation without transposition, respectively. $\otimes$ denotes the Kronecker operator, $\mathrm{vec}(\cdot)$ denotes a matrix operation that stacks the columns of a matrix under each other to form a new vector, $\mathrm{diag}(\cdot)$ denotes the diagonalization operation, $\arg(\gamma)$ denotes the phase of γ.

2. Signal model

Consider a narrowband monostatic MIMO radar system with M elements used for both transmit and receive arrays (Fig. 1). The transmit and receive arrays are assumed to be closely located so that a target located in the far-field can be seen by both of them at the same angle. All antennas are uniform linear arrays (ULAs) omnidirectional. The inter-element spaces of the transmit and receive arrays are half-wavelength. At the transmit array, all elements emit orthogonal noncircular signals, which have identical bandwidth and center frequency. It is assumed that the Doppler frequencies have no effect on the orthogonality of the waveforms and the variance of the phase within repetition intervals. Assume that the number of targets is known, and there are P uncorrelated targets located in the far-field of the array and in the same range bin. The signals arrived at the receive array through reflections of the targets can be described as

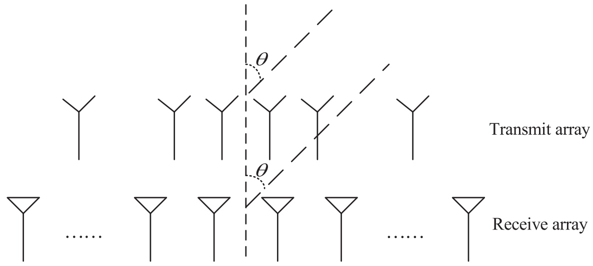

Fig. 1. The configuration of monostatic MIMO radar.

$$\boldsymbol{X} = \sum_{p=1}^{P} \beta_p \mathbf{a}(\theta_p)\mathbf{a}^{\mathrm{T}}(\theta_p)\mathbf{S} + \mathbf{W} \tag{1}$$

where β_p is the real-valued amplitude of the pth target, $\mathbf{a}(\theta_p) = [1\ e^{j\pi \sin\theta_p}\ \cdots\ e^{j\pi(M-1)\sin\theta_p}]^{\mathrm{T}} \in C^{M\times 1}$ is the steering vector of the pth target, $\mathbf{S} \in C^{M\times L}$ is the orthogonal and noncircular transmit signal matrix, and $\mathbf{W} \in C^{M\times L}$ is the complex Gaussian white noise vector with zeros mean and covariance matrix $\sigma^2\mathbf{I}$. Exploiting the orthogonality property of the transmitted waveforms, the received data can be processed by matched filtering using $\mathbf{S}^H$. The output of the matched filters can be written as [7]

$$\overline{\boldsymbol{X}} = \sum_{p=1}^{P} \beta_p \mathbf{a}(\theta_p)\mathbf{a}^{\mathrm{T}}(\theta_p) + \overline{\mathbf{W}} \tag{2}$$

where $\overline{\mathbf{W}} = \mathbf{W}\mathbf{S}^H$ is the noise matrix after matched filters. Stacking each succeeding column of $\overline{\boldsymbol{X}} \in C^{M\times M}$, we obtain the $M^2 \times 1$ virtual data vector

$$\mathbf{Y} = \mathrm{vec}(\overline{\mathbf{X}}) = \sum_{p=1}^{P} \beta_p \mathbf{b}(\theta_p) + \mathbf{N} \tag{3}$$

where $\mathbf{b}(\theta_p) = \mathbf{a}(\theta_p) \otimes \mathbf{a}(\theta_p) \in C^{M^2\times 1}$ is the transmit–receive steering vector, $\mathbf{N} = \mathrm{vec}(\overline{\mathbf{W}}) \in C^{M^2\times 1}$ is a zero-mean complex Gaussian white noise vector with covariance matrix $\sigma^2\mathbf{I}_{M^2\times 1}$. Owing to the fact that the radar system used a length K periodic pulse train to temporally sample the signal environment, the received data in Eq. (3) can be expressed as

$$\mathbf{Y}(k) = \mathbf{B}(\theta)\mathbf{H}(k) + \mathbf{N}(k), \quad k = 1,2,\ldots,K \tag{4}$$

where $\mathbf{B}(\theta) = [\mathbf{b}(\theta_1), \mathbf{b}(\theta_2), \ldots, \mathbf{b}(\theta_P)]$, $\mathbf{H}(k) = \mathrm{diag}[\beta_1(k), \beta_2(k), \ldots, \beta_P(k)]$ stands for the reflected noncircular signal of targets after matching filters, which satisfies with $\mathbf{H}(k) = \mathbf{H}^*(k)$ and are adopted in this paper, and $\mathbf{N}(k)$ is the noise vector for the k periodic pulse train.