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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

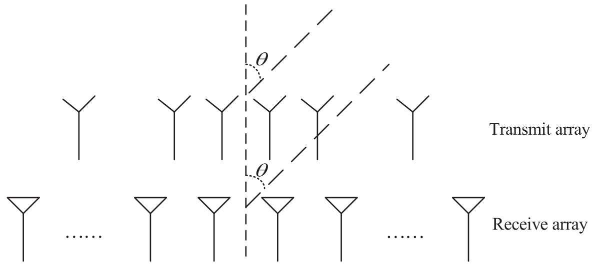

Fig. 1. The configuration of monostatic MIMO radar.

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

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.

3. Conjugate ESPRIT for DOA estimation

3.1. Reduced-dimensional matrix for monostatic MIMO radar

Owing to the fact that the transmit–receive steering vector has only $2M-1$ distinct elements [16], the transmit–receive steering vector can be the linear transformation of these $2M-1$ distinct elements, which can be expressed as

$$\mathbf{b}(\theta)=\mathbf{a}(\theta)\otimes\mathbf{a}(\theta)=\mathbf{F}\mathbf{g}(\theta) \tag{5}$$

where $\mathbf{g}(\theta)=[1\ e^{j\pi\sin\theta}\ \cdots\ e^{j\pi(2M-2)\sin\theta}]^{\mathrm{T}}$ is the steering vector of the virtual uniform linear array with $2M-1$ distinct elements, which only depends on M and θ. The transformation matrix $\mathbf{F}$ is

$$\mathbf{F}=\begin{bmatrix} \left.\begin{matrix} 1 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & 0 & \cdots & 0 \end{matrix}\right\}M \\ \left.\begin{matrix} 0 & 1 & 0 & \cdots & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & 1 & \cdots & 0 \end{matrix}\right\}M \\ \begin{matrix} \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{matrix} \\ \left.\begin{matrix} 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \\ 0 & \cdots & 0 & 0 & 1 & \cdots & 0 \\ \vdots & \cdots & \vdots & \cdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & 0 & 0 & \cdots & 1 \end{matrix}\right\}M \end{bmatrix}_{M^2\times(2M-1)} \tag{6}$$

According to Eq. (5), the transmit–receive steering matrix $\mathbf{B}(\theta)$ can be expressed as

$$\mathbf{B}(\theta)=\mathbf{F}\mathbf{G}(\theta) \tag{7}$$

where $\mathbf{G}(\theta)=[\mathbf{g}(\theta_1),\mathbf{g}(\theta_2),\ldots,\mathbf{g}(\theta_P)]$. Substituting Eq. (7) into Eq. (4), we can obtain

$$\mathbf{Y}(k)=\mathbf{F}\mathbf{G}(\theta)\mathbf{H}(k)+\mathbf{N}(k),\quad k=1,2,\ldots,K \tag{8}$$

From Eq. (8), we can observe that the target signals in the received data matrix $\mathbf{Y}(k)$ are located in the lower dimensional space spanned by $\mathbf{F}$. Thus, the received data matrix can be converted into the lower dimensional space which can be used to estimate the DOA of targets. A reduced-dimensional matrix $\mathbf{D}$ is designed to convert the received data into a lower-dimensional data matrix, which can be written as [13]

$$\overline{\mathbf{Y}}(k)=\mathbf{D}^{\mathrm{H}}\mathbf{Y}(k)=\mathbf{D}^{\mathrm{H}}\mathbf{F}\mathbf{G}(\theta)\mathbf{H}(k)+\mathbf{D}^{\mathrm{H}}\mathbf{N}(k),\quad k=1,2,\ldots,K \tag{9}$$

where span $\{\mathbf{D}\}=\mathrm{span}\{\mathbf{F}\}$, in order to preserve the reduced dimensional noise vector $\mathbf{D}^{\mathrm{H}}\mathbf{N}(k)$ still being a zero-mean Gaussian white noise vector with covariance matrix $\sigma^2\mathbf{I}_{(2M-1)}$, the reduced dimensional matrix must satisfy with $\mathbf{D}^{\mathrm{H}}\mathbf{D}=\mathbf{I}_{2M-1}$. Thus, the reduced dimensional matrix $\mathbf{D}$ can be chosen as [13]

$$\mathbf{D}=\mathbf{F}(\mathbf{F}^{\mathrm{H}}\mathbf{F})^{-1/2} \tag{10}$$

Substituting Eq. (10) into Eq. (9), we have

$$\overline{\mathbf{Y}}(k)=(\mathbf{F}^{\mathrm{H}}\mathbf{F})^{1/2}\mathbf{G}(\theta)\mathbf{H}(k)+\overline{\mathbf{N}}(k),\quad k=1,2,\ldots,K \tag{11}$$

where $(\mathbf{F}^{\mathrm{H}}\mathbf{F})=\overline{\mathbf{D}}=\mathrm{diag}([1,2,\ldots,M-1,M,M-1,..,1])$ is a $(2M-1)\times(2M-1)$ diagonal matrix, $\overline{\mathbf{N}}(k)=\mathbf{D}^{\mathrm{H}}\mathbf{N}(k)$ is the zero-mean Gaussian white noise vector with covariance matrix $\sigma^2\mathbf{I}_{(2M-1)}$. From Eq. (11), we can observe that the reduced-dimensional received data are equivalent to the received data of a linear array with $2M-1$ elements whose array weighting is $[1,\sqrt{2},\ldots,\sqrt{M-1},\sqrt{M},\sqrt{M-1},\ldots,1]$. These reduced dimensional received data will be used to estimate DOA of target in the following section.

3.2. Conjugate ESPRIT for DOA estimation

According to the reduced-dimensional received data in Eq. (11) and the properties of noncircular signals, a new received data of virtual array with $4M-2$ distinct elements is defined as

$$\mathbf{Z}(k)=\begin{bmatrix}\boldsymbol{\Gamma}_{(2M-1)}\overline{\mathbf{Y}}^*(k)\\ \overline{\mathbf{Y}}(k)\end{bmatrix}=\begin{bmatrix}\boldsymbol{\Gamma}_{(2M-1)}\overline{\mathbf{D}}\mathbf{G}^*(\theta)\mathbf{H}^*(k)\\ \overline{\mathbf{D}}\mathbf{G}(\theta)\mathbf{H}(k)\end{bmatrix}+\begin{bmatrix}\boldsymbol{\Gamma}_{(2M-1)}\mathbf{N}^*(k)\\ \mathbf{N}(k)\end{bmatrix},\quad k=1,2,\ldots,K \tag{12}$$

where $\boldsymbol{\Gamma}_{(2M-1)}\in C^{(2M-1)\times(2M-1)}$ is the exchange matrix with ones on its antidiagonal and zeros elsewhere, and $\boldsymbol{\Gamma}_{(2M-1)}\boldsymbol{\Gamma}_{(2M-1)}=\mathbf{I}_{(2M-1)}$. Using the properties of noncircular signals and exchange matrix $\boldsymbol{\Gamma}_{(2M-1)}$, Eq. (12) can be rewritten as

$$\mathbf{Z}(k)=\overline{\mathbf{F}}\hat{\mathbf{G}}(\theta)\mathbf{H}(k)+\overline{\mathbf{N}}(k),\quad k=1,2,\ldots,K \tag{13}$$

where

$$\overline{\mathbf{F}}=\begin{bmatrix}\boldsymbol{\Gamma}_{(2M-1)}\overline{\mathbf{D}}\boldsymbol{\Gamma}_{(2M-1)} & \mathbf{0}_{(2M-1)}\\ \mathbf{0}_{(2M-1)} & \overline{\mathbf{D}}\end{bmatrix} \tag{14}$$

$$\hat{\mathbf{G}}(\theta)=\begin{bmatrix}\boldsymbol{\Gamma}_{(2M-1)}\mathbf{G}^*(\theta)\\ \mathbf{G}(\theta)\end{bmatrix},\quad \overline{\mathbf{N}}(k)=\begin{bmatrix}\boldsymbol{\Gamma}_{(2M-1)}\mathbf{N}^*(k)\\ \mathbf{N}(k)\end{bmatrix} \tag{15}$$

where $\overline{\mathbf{F}}$ is also a diagonal matrix. Let $\mathbf{G}_1(\theta)$ and $\mathbf{G}_2(\theta)$ are the first and last $2M-2$ rows of $\mathbf{G}(\theta)$. According to the structure of $\hat{\mathbf{G}}(\theta)$, we have

$$\begin{bmatrix}\boldsymbol{\Gamma}_{(2M-2)}\mathbf{G}_2^*(\theta)\\ \mathbf{G}_2(\theta)\end{bmatrix}=\begin{bmatrix}\boldsymbol{\Gamma}_{(2M-2)}\mathbf{G}_1^*(\theta)\\ \mathbf{G}_1(\theta)\end{bmatrix}\boldsymbol{\Phi} \tag{16}$$

where $\boldsymbol{\Phi}=\mathrm{diag}[e^{j\pi\sin\theta_1}\ e^{j\pi\sin\theta_2}\ \cdots\ e^{j\pi\sin\theta_P}]$ is a diagonal matrix, the diagonal elements of which contain the DOA information of targets. From Eq. (16), it can be concluded that $\hat{\mathbf{G}}_1(\theta)$ and $\hat{\mathbf{G}}_2(\theta)$ have the rotational invariance property, which is employed in this paper for DOA estimation, where $\hat{\mathbf{G}}_1(\theta)$ and $\hat{\mathbf{G}}_2(\theta)$ are defined as

$$\hat{\mathbf{G}}_1(\theta)=\begin{bmatrix}\boldsymbol{\Gamma}_{(2M-2)}\mathbf{G}_1^*(\theta)\\ \mathbf{G}_1(\theta)\end{bmatrix}=\boldsymbol{\Pi}_1\hat{\mathbf{G}}(\theta) \tag{17}$$

$$\hat{\mathbf{G}}_2(\theta)=\begin{bmatrix}\boldsymbol{\Gamma}_{(2M-2)}\mathbf{G}_2^*(\theta)\\ \mathbf{G}_2(\theta)\end{bmatrix}=\boldsymbol{\Pi}_2\hat{\mathbf{G}}(\theta) \tag{18}$$

where $\boldsymbol{\Pi}_1$ and $\boldsymbol{\Pi}_2$ are the selection matrices, both of which are formulated as

$$\boldsymbol{\Pi}_1=\begin{bmatrix}\mathbf{K}_1 & \mathbf{0}_{(2M-2)\times(2M-1)}\\ \mathbf{0}_{(2M-2)\times(2M-1)} & \mathbf{K}_1\end{bmatrix} \tag{19}$$

$$\mathbf{\Pi}_2 = \begin{bmatrix} \mathbf{K}_2 & \mathbf{0}_{(2M-2)\times(2M-1)} \\ \mathbf{0}_{(2M-2)\times(2M-1)} & \mathbf{K}_2 \end{bmatrix} \tag{20}$$

where $\mathbf{K}_1 = [\mathbf{I}_{2M-2}, \mathbf{0}_{(2M-2)\times 1}]$, $\mathbf{K}_2 = [\mathbf{0}_{(2M-2)\times 1}, \mathbf{I}_{2M-2}]$. The ML estimation of the covariance matrix is written as

$$\mathbf{R} = \frac{1}{K}\sum_{k=1}^{K} \mathbf{Z}(k)\mathbf{Z}^{\mathrm{H}}(k) \tag{21}$$

The singular value decomposition (SVD) of the real covariance matrix $\mathbf{R}$ can be written as

$$\mathbf{R} = [\mathbf{E}_s \ \ \mathbf{E}_n]\begin{bmatrix} \mathbf{\Sigma} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}\mathbf{V}^{\mathrm{H}} \tag{22}$$

where $\mathbf{E}_s$ is an $(4M-2)\times P$ signal subspace matrix which is composed of left singular vectors corresponding to the nonzero singular values, $\mathbf{E}_n$ is an $(4M-2)\times(4M-2-P)$ noise subspace matrix which is composed of left singular vectors corresponding to the zero singular values, $\mathbf{\Sigma}$ is a $P\times P$ diagonal matrix with the nonzero singular values, and $\mathbf{V}$ is a matrix which is composed of right singular vectors corresponding to all the singular values. In the noise-free case, as we know, the signal subspace $\mathbf{E}_s$ can be spanned by $\overline{\mathbf{F}}\hat{\mathbf{G}}(\theta)$, which can be expressed as

$$\mathbf{E}_s = \overline{\mathbf{F}}\hat{\mathbf{G}}(\theta)\mathbf{T} \tag{23}$$

where $\mathbf{T}$ is $P\times P$ nonsingular matrix. Due to the fact that the $(2M-2)\times(2M-2)$ matrix $\overline{\mathbf{F}}$ is a diagonal matrix, the modified signal subspace can be derived as

$$\overline{\mathbf{E}}_s = \overline{\mathbf{F}}^{-1}(\theta)\mathbf{E}_s = \hat{\mathbf{G}}(\theta)\mathbf{T} \tag{24}$$

From Eq. (24), we can observe that the modified signal subspace $\overline{\mathbf{E}}_s$ is spanned by $\hat{\mathbf{G}}(\theta)$. Thus, let $\overline{\mathbf{E}}_{s1} = \mathbf{\Pi}_1\overline{\mathbf{E}}_s$ and $\overline{\mathbf{E}}_{s2} = \mathbf{\Pi}_2\overline{\mathbf{E}}_s$, the rotational invariance property between $\overline{\mathbf{E}}_{s2}$ and $\overline{\mathbf{E}}_{s1}$ can be written as

$$\overline{\mathbf{E}}_{s2} = \overline{\mathbf{E}}_{s1}\mathbf{\Psi} \tag{25}$$

where $\mathbf{\Psi} = \mathbf{Q}^{-1}\mathbf{\Phi}\mathbf{Q}$, the columns of $\mathbf{Q}$ are the eigenvectors of $\mathbf{\Psi}$. From Eq. (25), it can be concluded that the virtual array elements of $\overline{\mathbf{E}}_{s1}$ and $\overline{\mathbf{E}}_{s2}$ are $4M-4$ which is twice that of the subarrays in [13]. Thus, the proposed method provides better angular estimation accuracy. Eq. (25) can be solved by the least squares (LS) or the total least squares (TLS) algorithm. Then the estimated diagonal matrix $\hat{\mathbf{\Phi}}$ can be obtained by the eigenvalue decomposition of $\mathbf{\Psi}$. Thus, the DOA θ_p for the pth target can be written as

$$\theta_p = \arcsin[\arg(\hat{\gamma}_p)/\pi], \quad p = 1,2,\ldots,P \tag{26}$$

where $\hat{\gamma}_p$ is the pth diagonal elements of $\hat{\mathbf{\Phi}}$. According to Eq. (25), the virtual elements corresponding to the signal subspace $\overline{\mathbf{E}}_{s2}$ or $\overline{\mathbf{E}}_{s1}$ are $4M-4$. Thus, the maximum number of identified targets by the proposed is $4M-4$ while RD-ESPRIT is $2M-2$.

Up to now, we have achieved the conjugate ESPRIT for DOA estimation in monostatic MIMO radar, the procedure of our algorithm is summarized as following:

(1) matched filter using $\mathbf{S}^{\mathrm{H}}$ to obtain the received data vector $\mathbf{Y}(k) \in C^{M^2\times 1}$;
(2) convert the received data vector $\mathbf{Y}(k) \in C^{M^2\times 1}$ into lower-dimensional data vector $\overline{\mathbf{Y}}(k) \in C^{(2M-1)\times 1}$ by using the reduced dimensional matrix $\mathbf{D}$;
(3) construct the new received data vector $\mathbf{Z}(k) \in C^{(4M-2)\times 1}$ shown in Eq. (12);
(4) estimate the covariance matrix $\mathbf{R}$ and compute the signal subspace $\mathbf{E}_s$ by SVD of $\mathbf{R}$;
(5) compute the modified signal subspace $\overline{\mathbf{E}}_s$ using Eq. (24), and construct $\overline{\mathbf{E}}_{s2}$ and $\overline{\mathbf{E}}_{s1}$;
(6) utilize eigenvalue decomposition of $\mathbf{\Psi}$ to estimate $\hat{\mathbf{\Phi}}$, finally estimate DOA using Eq. (26).

3.3. Computational complexity analysis

In contrast to ESPRIT and RD-ESPRIT, the computational load of the proposed method is usually dominated by formation of the covariance matrix and calculation of EVD. The major computation complexity of the proposed method is $0((4M-2)^2K+(4M-2)^3+P^3)$, while ESPRIT and RD-ESPRIT require $0(M^4K+M^5+P^3)$ and $0((2M-1)^2K+(2M-1)^3+P^3)$, respectively. In the typical circumstances, the number of virtual elements M^2 is satisfied with $M^2 \geqslant 4M-2$. Thus, the proposed method has a low computational load than ESPRIT. Owing to the added virtual elements, the proposed method has higher computational complexity than RD-ESPRIT, but the proposed method provides better angle estimation performance than both RD-ESPRIT and ESPRIT.

4. Simulation results

In this section, several numerical examples are presented to verify the effectiveness of the proposed method. Consider a monostatic MIMO radar system with $M=5$ elements used for both transmit and receive arrays. Both the transmit and receive arrays are ULA, and the inter-element spaces of the transmit and receive arrays are half-wavelength. Three noncoherent narrowband signal sources coming from $\theta_1 = 10°$, $\theta_2 = -10°$ and $\theta_3 = -20°$ are considered. Several examples are used to compare the performance of the ESPRIT [8] and RD-ESPRIT [13] method. Define the root mean squared error (RMSE) as

$$\mathrm{RMSE}(\theta) = \frac{1}{P}\sum_{P=1}^{P}\sqrt{\frac{1}{L}\sum_{l=1}^{L}(\hat{\theta}_{p,l}-\theta_p)} \tag{27}$$

where L is the number of Monte Carlo trials, $\hat{\theta}_{p,l}$ is the estimation of DOA θ_p of the lth Monte Carlo trial.

The DOA estimation RMSE and the probabilities of target resolution versus SNR are shown for all methods tested in Figs. 2 and 3, respectively, where the number of snapshots is 200, and $L=200$ independent trials are used. Fig. 2 shows a comparison on the RMSE for signal sources against the SNR. It is observed that the angular estimation accuracy of the RD-ESPRIT method is only improved slightly compared with ESPRIT at low SNR region while the RMSE of C-ESPRIT is lower than both aforementioned methods at all SNR region. Fig. 3 shows the probability estimation of source resolution for the three aforementioned methods. From Fig. 3, we can see that the RD-ESPRIT algorithm has better source resolution capabilities than the ESPRIT method at low SNR region while

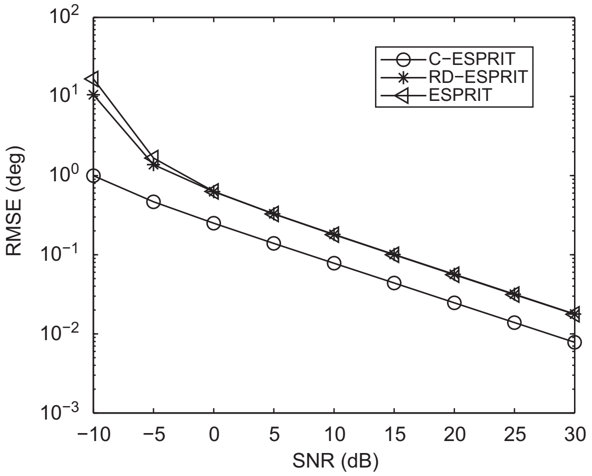

Fig. 2. RMSE versus SNR for $P=3$ targets.

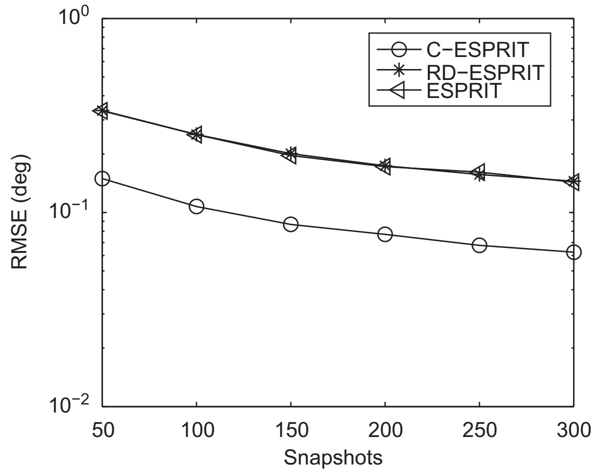

Fig. 4. RMSE versus snapshots for $P=3$ targets.

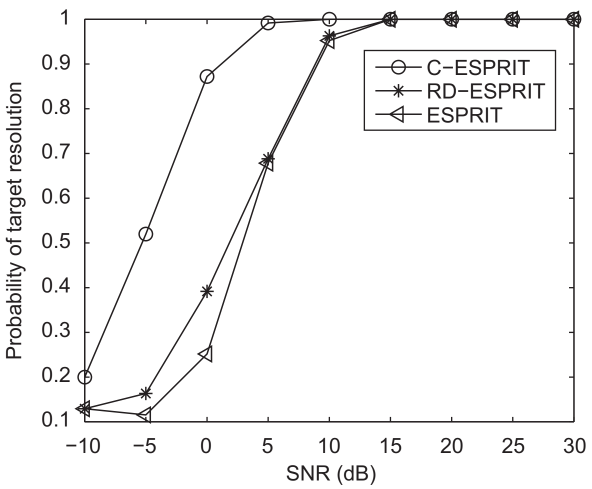

Fig. 3. Probability of target resolution versus SNR.

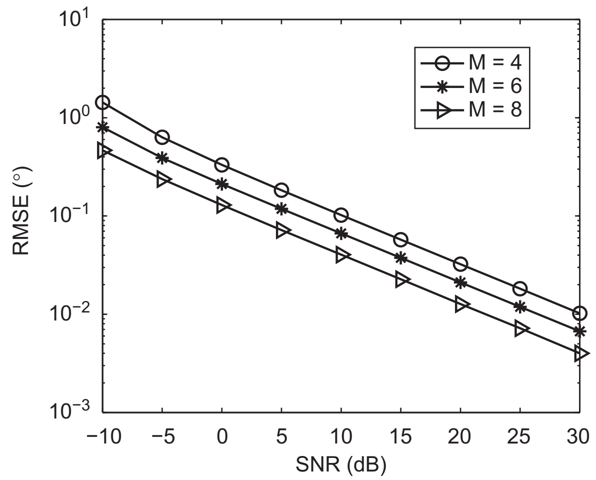

Fig. 5. RMSE versus SNR for different sensors.

the C-ESPRIT is superior to both methods. Owing to the fact that the RD-ESPRIT method is a reduced dimension beamspace of ESPRIT, the RD-ESPRIT has better angle estimation performance than ESPRIT at low region. The virtual array elements of C-ESPRIT are twice as many as RD-ESPRIT method, so the angle estimation performance of the C-ESPRIT method is superior to both RD-ESPRIT and ESPRIT.

Fig. 4 shows a comparison on the RMSE for three targets against snapshots, where the SNR of three targets is 10 dB, and $L=200$ independent trials are used. It can be observed that the RMSE of the RD-ESPRIT is the same as ESPRIT while C-ESPRIT method has lower RMSE than both of them.

Fig. 5 shows the RMSE for angle estimation with different sensors. From Fig. 5, we can observe that the angle estimation performance is remarkably improved with the sensors increasing. Owing to the number of virtual array elements is increased in the proposed method, the more diversity gain is obtained, and the angle estimation performance is improved.

According to Eq. (25), the maximum number of identified targets by C-ESPRIT is $4M-4$ while RD-ESPRIT is $2M-2$. The proposed method can identify four targets with $M=2$ sensors, while the RD-ESPRIT algorithm can only two targets. Fig. 6 shows that the angle estimation results for four targets with $M=2$ by the proposed method, where the SNR of four targets are 10 dB. From Fig. 6 we can see that the DOAs of four targets are estimated correctly by the proposed method. So C-ESPRIT can detect more targets than RD-ESPRIT.

5. Conclusion

In this paper, a conjugate ESPRIT method for DOA estimation in monostatic MIMO radar is presented. The proposed method converts the received data into a reduced dimensional space, and the rotational invariance property of the constructed virtual array, whose elements are twice as many as monostatic MIMO radar virtual array with distinct elements, is used to estimate the DOA of target. Therefore, the proposed method has

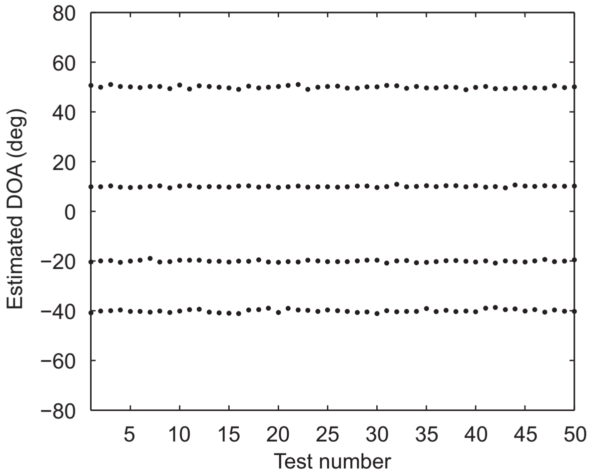

Fig. 6. Angle estimation results for four targets with $M=2$.

better angle estimation performance and can detect more targets than RD-ESPRIT. Several simulation results have verified the performance of the proposed method.

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