Signal Processing 92 (2012) 198–203

Contents lists available at ScienceDirect

Signal Processing

journal homepage: www.elsevier.com/locate/sigpro

Direction finding with automatic pairing for bistatic MIMO radar

Rong Xie *, Zheng Liu, Jian-xin Wu

National Laboratory of Radar Signal Processing, Xidian University, 710071 Xi' an, China

ARTICLE INFO

Article history:
Received 8 March 2011
Received in revised form
1 July 2011
Accepted 5 July 2011
Available online 19 July 2011

Keywords:
Direction finding
Bistatic MIMO radar
Automatic pairing
Quadratic form

ABSTRACT

Direction finding is an important issue for bistatic MIMO radar. A two-dimensional direction finding method with automatic pairing is developed. In the presented method, the property of the kronecker product is first utilized to reformulate the cost function in the quadratic form. Then, by constructing the orthogonality constraint of the target DOA to the quadratic form, all target DODs can be first estimated by solving the constrained quadratic form. Moreover, the *p*th target DOA can be directly estimated by the eigenvector which is related to the *p*th target DOD. Thus, the target DOD and DOA can be automatically paired. Finally, simulation results demonstrate that the effectiveness of the presented method.

1. Introduction

Multiple-input multiple-output (MIMO) radar [1], which uses multiple antennas to simultaneously transmit diverse waveforms and multiple antennas to receive the reflected signals, has been widely investigated in recent years, owing to a number of potential advantages over the conventional phased-array radar, such as more sensitivity to detect slowly moving targets [2], better parameter identifiability [2], and increased angular resolution [3]. Direction of departure (DOD) and direction of arrival (DOA) estimation is an important aspect for bistatic MIMO radar and a variety of methods are developed [3–13]. A maximum likelihood estimator for target localization is firstly derived in Ref. [3]. This estimator is computationally expensive for its multidimensional search. In Ref. [4], the two-dimensional Capon estimator is introduced to estimate the DOAs and the DODs of the targets in bistatic MIMO radar. However, in order to acquire high angle estimation accuracy, the presented method needs two-dimensional fine angle search. To alleviate the computational burden, an ESPRIT algorithm is employed utilizing the rotational invariance property of the transmit and receive arrays [5]. Whereas it requires the additional pairing procedure. To realize the auto-pairing between the DOAs and the DODs, the interrelationship between the two one-dimensional ESPRIT is investigated in Ref. [6]. In Ref. [7], an ESPRIT-based algorithm is proposed which exploits both the invariance property and the signal subspace of the receive array for multi-target localization without pairing in bistatic MIMO radar. In Ref. [8], an algorithm based on the combined ESPRIT-MUSIC approach to estimate the transmit angles and receive angles of targets without pairing in bistatic MIMO radar is proposed. In Ref. [9], the ESPRIT method is also applied to the bistatic MIMO radar to estimate target angles using the rotational factor produced by multi-transmitter. In Ref. [10], the angle estimation method employing ESPRIT and SVD of cross-correlation matrix of the received data from two transmit subarrays is developed. It performs well even under the spatial colored noise environment. Additionally, a tri-iterative least-square (TI-LS) method is proposed in Ref. [11] for angle estimation in MIMO radar, where the transmit and receive steering matrices are iteratively determined under the LS criterion. In Ref. [12], a reduced-dimensional MUSIC (RD-MUSIC) algorithm is proposed which employs one-dimensional search to avoid the high computational

* Corresponding author.
E-mail address: rxie@mail.xidian.edu.cn (R. Xie).

0165-1684/$ - see front matter
doi:10.1016/j.sigpro.2011.07.004

cost resulted from the conventional two-dimensional MUSIC (2D -MUSIC) algorithm. However, this method suffers some performance degradation since there is an approximation on the receiving steering vector. The algorithm has better performance than the ESPRIT algorithm with no pair matching. In Ref. [13], an algorithm based on double polynomial root finding procedure to estimate the DOA and DOD is proposed. The proposed method allows an efficient estimation of the target DOA and DOD with automatic pairing.

In this communication, a two-dimensional direction finding method with automatic pairing for bistatic MIMO radar is developed, which has asymptotical identical performance with the conventional 2D-MUSIC method and can be considered as fast implementation of the conventional 2D-MUSIC method. In the present method, the property of the kronecker product is first utilized to reformulate the cost function in the quadratic form. Then, by constructing the orthogonal constraint associated with the target DOA to the quadratic form, all target DODs can be first estimated by solving the constrained quadratic form. Moreover, the pth target DOA can be directly estimated by the eigenvector which is related to the pth target DOD. Thus, the target DOD and DOA can be automatically paired.

2. Problem formulation

Consider a bistatic MIMO radar system with M closely transmitting antennas and N closely receiving antennas, both of which are uniform linear arrays (ULAs) with half-wavelength spacing. The transmitting antennas transmit orthogonal waveforms with identical bandwidth and center frequency. Assume that there are P non-coherent targets located in the far-field of the arrays and in the same range bin. The directions of the pth target with respect to the transmitting array normal and the receiving array normal are denoted by angles θ_p and ϕ_p, respectively. Thus, the location of the pth target can be denoted by (θ_p,ϕ_p). Then the output of the matched filters can be written as [5]

$$\mathbf{r}(t)=\mathbf{A}(\theta,\phi)\mathbf{s}(t)+\mathbf{n}(t) \tag{1}$$

where $\mathbf{A}(\theta,\phi)=[\mathbf{a}_t(\theta_1)\otimes\mathbf{a}_r(\phi_1),\mathbf{a}_t(\theta_2)\otimes\mathbf{a}_r(\phi_2),\cdots,\mathbf{a}_t(\theta_P)\otimes\mathbf{a}_r(\phi_P)]$ is the transmit-receive array manifold, $\mathbf{a}_t(\theta_p)=[e^{j\alpha_1(\theta_p)},e^{j\alpha_2(\theta_p)},\ldots,e^{j\alpha_M(\theta_p)}]^T$ and $\mathbf{a}_r(\phi_p)=[e^{j\beta_1(\phi_p)},e^{j\beta_2(\phi_p)},\ldots,e^{j\beta_N(\phi_p)}]^T$ are the transmitting and receiving steering vectors, respectively, $\alpha_m(\theta_p)=\pi(m-1)\sin\theta_p$, $m=1,2,\ldots,M$, $\beta_n(\phi_p)=\pi(n-1)\sin\phi_p$, $n=1,2,\ldots,N$. $\otimes$ denotes the Kronecker product, and $[\cdot]^T$ denotes the transpose operation. $\mathbf{s}(t)=[s_1(t),s_2(t),\ldots,s_P(t)]^T$ is a $P\times 1$ vector, where $s_p(t)=\alpha_p e^{j\omega_d t}$ with ω_d being the Doppler frequency and α_p the target amplitude determined by the target RCS. $\mathbf{n}(t)$ denotes an $NM\times 1$ noise vector, which is assumed to obey the zero-mean complex Gaussian distribution with covariance matrix $\sigma^2\mathbf{I}$.

3. Two-dimensional angle estimation with automatic pairing

According to the signal model developed in Eq. (1), two-dimensional direction finding for bistatic MIMO radar can be realized by the conventional 2D –MUSIC algorithm. That is

$$\hat{P}_{2D-MUSIC}(\theta,\phi)=\frac{1}{(\mathbf{a}_t(\theta)\otimes\mathbf{a}_r(\phi))^H\mathbf{E}_n{\mathbf{E}_n}^H(\mathbf{a}_t(\theta)\otimes\mathbf{a}_r(\phi))} \tag{2}$$

where $\mathbf{E}_n$ is the noise space spanned by NM-P eigenvectors corresponding to the minimal NM-P eigenvalues of the covariance matrix, $[\cdot]^H$ denotes complex conjugate transpose operation. To obtain all target directions, an exhaustive search in the two-dimensional space is generally required, thus leading to great computational burden. Here, utilizing the property of the Kronecker product, fast implementation of the two-dimensional angle estimation can be realized without the exhaustive two-dimensional search.

First, utilizing the property of the Kronecker product, the transmit-receive steering vector can be reformulated as

$$\mathbf{a}_t(\theta)\otimes\mathbf{a}_r(\phi)=(\mathbf{a}_t(\theta)\otimes\mathbf{I}_N)\mathbf{a}_r(\phi) \tag{3}$$

Inserting Eq. (3) into Eq. (2), we get

$$\hat{P}_{2D-MUSIC}(\theta,\phi)=\frac{1}{\mathbf{a}_r(\phi)^H(\mathbf{a}_t(\theta)\otimes\mathbf{I}_N)^H\mathbf{E}_n{\mathbf{E}_n}^H(\mathbf{a}_t(\theta)\otimes\mathbf{I}_N)\mathbf{a}_r(\phi)} \tag{4}$$

Define

$$\mathbf{Q}(\theta)=(\mathbf{a}_t(\theta)\otimes\mathbf{I}_N)^H\mathbf{E}_n{\mathbf{E}_n}^H(\mathbf{a}_t(\theta)\otimes\mathbf{I}_N) \tag{5}$$

where $\mathbf{Q}(\theta)$ is an $N\times N$ Hermitian matrix dependent on θ and independent on ϕ. According to Eq. (4), we define the following cost function:

$$J(\phi,\theta)=\mathbf{a}_r(\phi)^H\mathbf{Q}(\theta)\mathbf{a}_r(\phi) \tag{6}$$

And two-dimensional angle estimation can be carried out by

$$[\hat{\phi},\hat{\theta}]=\min_{\hat{\phi},\hat{\theta}}J(\phi,\theta) \tag{7}$$

Observing from Eq. (6), we find that θ and ϕ are decoupled in the cost function, which is beneficial to angle estimation with low complexity. To realize decoupled angle estimation, a simple and efficient method is to convert the unconstrained optimization problem in Eq. (7) to a constrained optimization problem which is expressed in the form

$$\min_{\theta}\quad J(\phi,\theta),$$

$$s.t.\quad \mathbf{a}_r(\phi)^H\mathbf{P}=1 \tag{8}$$

where $\mathbf{P}\neq\mathbf{0}_{N\times 1}$ is a constrained vector to avoid $\mathbf{a}_r(\phi)$ tending to be the zero vector. By constructing different forms of $\mathbf{P}$, we can obtain different angle estimation methods. Here, three forms of $\mathbf{P}$ are considered to realize decoupled angle estimation.

Case one: $\mathbf{P}=\mathbf{a}_r(\phi_0)$, where ϕ_0 is the assumed DOA. Then Eq. (8) is converted to the linear constraint optimization problem. Using Lagrange multipliers, a cost function can be reconstructed as

$$L(\theta,\phi)=J(\phi,\theta)-\lambda(\mathbf{a}_r(\phi)^H\mathbf{a}_r(\phi_0)-1) \tag{9}$$