Journal of Systems Engineering and Electronics
Vol. 28, No. 4, August 2017, pp.697 – 702

Temporal-spatial subspaces modern combination method for 2D-DOA estimation in MIMO radar

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Abstract: A 2D-direction of arrival estimation (DOAE) for multi-input and multi-output (MIMO) radar using improved multiple temporal-spatial subspaces in estimating signal parameters via rotational invariance techniques method (TS-ESPRIT) is introduced. In order to realize the improved TS-ESPRIT, the proposed algorithm divides the planar array into multiple uniform sub-planar arrays with common reference point to get a unified phase shifts measurement point for all sub-arrays. The TS-ESPRIT is applied to each sub-array separately, and in the same time with the others to realize the parallelly temporal and spatial processing, so that it reduces the non-linearity effect of model and decreases the computational time. Then, the time difference of arrival (TDOA) technique is applied to combine the multiple sub-arrays in order to form the improved TS-ESPRIT. It is found that the proposed method achieves high accuracy at a low signal to noise ratio (SNR) with low computational complexity, leading to enhancement of the estimators performance.

Keywords: direction of arrival estimation (DOAE), temporal subspace, spatial subspace, estimating signal parameters via rotational invariance technique (ESPRIT).

DOI: 10.21629/JSEE.2017.04.09

1. Introduction

The direction of arrival estimation (DOAE) of the multiple narrowband signals is important in array signal processing including sonar, radar, astronomy and mobile communications.

In a radar tracking system, the target exact position determination during the initial detections is associated with the DOAE accuracy. Thus, the DOAE error affects the radar tracking system performance.

The ESPRIT and its extensions [1–11] have been widely studied in one-dimensional (1D) DOAE for uniform linear array (ULA), and non-uniform linear array (NULA), and also extended to two-dimensional (2D) DOAE [12–19]. The main drawback of these methods is the high computational costs associated with the high DOAE accuracy. Additionally these methods have a poor performance at a low signal to noise ratio (SNR). This paper presents a modern algorithm based on combination between time subspace ESPRIT (T-ESPRIT) [1,2] and spatial subspace ESPRIT (S-ESPRIT) via using the TDOA technique, which enhances the estimates performance specially at low SNR due to the using of the improved TS-ESPRIT method that enables multiple phase deference measurements with different resolutions. Firstly, the spatial subspace is realized by arranging the main planar array as a multiple uniform sub-planar arrays related to the common reference point to get a unified phase shifts measurement point for all sub-arrays. The TS-ESPRIT is simultaneously applied on all sub-arrays to realize the parallelly temporal and spatial processing, so that it reduces the non-linearity effect of the model and decreases the computational time. Then, the TDOA is applied to combine the multiple sub-arrays to calculate the optimum DOAE value at the reference antenna, which can enhance the estimation accuracy and reduce the computational load.

2. Proposed algorithm

2.1 Measurement model

In this model, the radiation propagates in straight lines due to the isotropic and non-dispersive transmission medium assumption. Also, it is assumed that the sources are far-field signals. Consequently, the radiation impinging on the array is a summation of the plane waves. The signals are assumed to be narrow-band, and they can be considered as sample functions of a stationary stochastic process or deterministic functions of time. Considering there are K narrow-band signals and the center frequency ω_0 is $\omega_0 = 2\pi f$, the kth signal can be written as

$$s_k(t) = E_k \mathrm{e}^{\mathrm{j}(\omega_0 t + \psi_k)}, \quad k = 1, 2, \ldots, K \qquad (1)$$

Manuscript received December 02, 2015.

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This work was supported by the National Natural Science Foundation of China (61301211) and the Aviation Science Foundation (20131852028).

where $s_k(t)$ is the signal of the kth emitting source at t, ψ_k is the carrier phase angle assumed to be a random variable distributed uniformly on $[0, 2\pi]$ and independent from each other.

Fig. 1 introduces a planar array arranged as sub-planar arrays and indexed with N, G along y and x directions respectively.

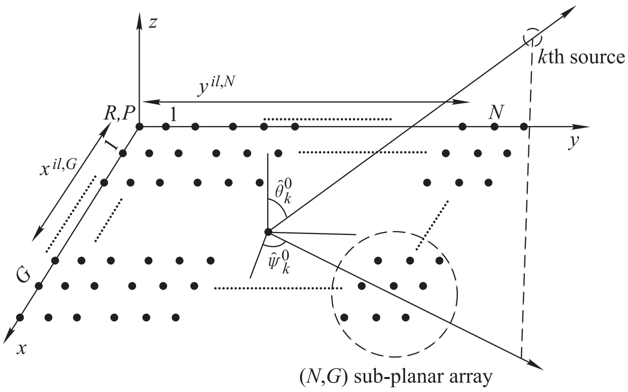

Fig. 1 Planar antenna array

Fig. 2 shows an (n, g) sub-planar array, where $n = 1, \dots, N$, and $g = 1, \dots, G$ have elements indexed L, I along y and x directions respectively. For any pair (i, l), its coordinates with respect to the reference point (R.P) along y and x directions respectively are $(y^{ii,n}, x^{ii,g})$, where $i = 1, \dots, I, l = 1, \dots, L$.

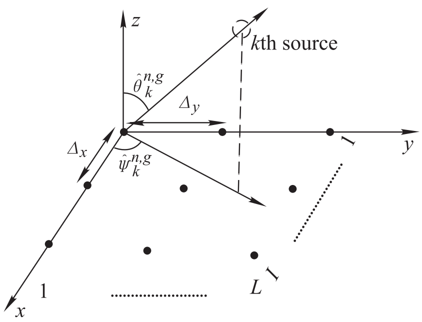

Fig. 2 Sub-planar antenna array

The space phase factors along x and y directions are expressed as

$$p_i(\theta_k^{n,g}, \varphi_k^{n,g}) \equiv p_i^k(n, g) = \mathrm{e}^{\mathrm{j}\frac{2\pi(i-1)\Delta_x}{\lambda}} \sin\theta_k^{n,g} \cos\varphi_k^{n,g} \tag{2}$$

$$x^{ii,g} = ((i-1)\Delta_x) + ((g-1)I\Delta_x) \tag{3}$$

$$q_i(\theta_k^{n,g}, \varphi_k^{n,g}) \equiv q_i^k(n, g) = \mathrm{e}^{\mathrm{j}\frac{2\pi(l-1)\Delta_y}{\lambda}} \sin\theta_k^{n,g} \sin\varphi_k^{n,g} \tag{4}$$

$$y^{ii,n} = ((l-1)\Delta_y) + ((n-1)L\Delta_y) \tag{5}$$

where $(\theta_k^{n,g}, \varphi_k^{n,g})$ denotes the kth source estimated elevation angle and azimuth angle respectively with respect to the (n, g) sub-array, Δ_x and Δ_y are reference displacements between neighbor elements along x and y directions within any (n, g) sub-array, also Δ_x and Δ_y are reference displacements between neighbor sub-arrays along x and y directions respectively, and λ is the wavelength of the signal. The receiving model can be expressed as

$$\boldsymbol{Z}^{n,g}(t) = \boldsymbol{A}^{n,g}\boldsymbol{S}(t) + \boldsymbol{W}(t) \tag{6}$$

where the matrices $\boldsymbol{S}(t), \boldsymbol{A}$ and $\boldsymbol{W}(t)$ are the receiving signal, transform factor for each sub-array, and additive white Gaussian noise (AWGN), respectively. They are given in the subspace as follows:

$$\boldsymbol{Z}^{n,g}(t) = [z_{1,1}^{n,g}(t) \cdots z_{1,L}^{n,g}(t) \cdots z_{I,1}^{n,g}(t) \cdots z_{I,L}^{n,g}(t)]^{\mathrm{T}} \tag{7}$$

$$\begin{aligned}\boldsymbol{A}^{n,g} &\overset{\text{def}}{=\!=} [\boldsymbol{u}_k^{\mathrm{T}}(\gamma_k, \eta_k, \theta_k^{n,g}, \varphi_k^{n,g}) \otimes \\ &p_i(\theta_k^{n,g}, \varphi_k^{n,g}) \otimes q_l(\theta_k^{n,g}, \varphi_k^{n,g})]\end{aligned} \tag{8}$$

where $\otimes$ denotes the Kronker product. Then, for any (n, g) sub-array, we have

$$\begin{aligned}\boldsymbol{A}^{n,g} = \boldsymbol{A}(\theta_k^{n,g}, \varphi_k^{n,g}) = [&\boldsymbol{U}_k^{\mathrm{T}} p_1^k q_1^k\ \boldsymbol{U}_k^{\mathrm{T}} p_1^k q_2^k \cdots \\ &\boldsymbol{U}_k^{\mathrm{T}} p_1^k q_L^k\ \boldsymbol{U}_k^{\mathrm{T}} p_2^k q_1^k\ \boldsymbol{U}_k^{\mathrm{T}} p_2^k q_2^k \cdots \boldsymbol{U}_k^{\mathrm{T}} p_2^k q_L^k \cdots \\ &\boldsymbol{U}_k^{\mathrm{T}} p_l^k q_1^k\ \boldsymbol{U}_k^{\mathrm{T}} p_l^k q_2^k \cdots \boldsymbol{U}_k^{\mathrm{T}} p_l^k q_L^k]^{\mathrm{T}}\end{aligned} \tag{9}$$

where $p_i(\theta_k^{n,g}, \varphi_k^{n,g})$ and $q_l(\theta_k^{n,g}, \varphi_k^{n,g})$ are symbolized as p_i^k, q_l^k. And,

$$\boldsymbol{U}_k^{\mathrm{T}} = u_k(\gamma_k, \eta_k, \theta_k^{n,g}, \varphi_k^{n,g}) =$$

$$\begin{pmatrix} \sin\gamma_k \cos\theta_k^{n,g} \cos\varphi_k^{n,g} \mathrm{e}^{\mathrm{j}\eta_k} - \cos\gamma_k \sin\varphi_k^{n,g} \\ \sin\gamma_k \cos\theta_k^{n,g} \sin\varphi_k^{n,g} \mathrm{e}^{\mathrm{j}\eta_k} + \cos\gamma_k \cos\varphi_k^{n,g} \end{pmatrix} \tag{10}$$

$$\boldsymbol{S}(t) \overset{\text{def}}{=\!=} [s_1(t) \quad \cdots \quad \cdots \quad s_K(t)]^{\mathrm{T}} \tag{11}$$

$$\boldsymbol{W}(t) = [w_{1.1}(t) \cdots w_{1,L}(t) \cdots w_{l,1}(t) \cdots w_{l,L}(t)]^{\mathrm{T}}. \tag{12}$$

The auxiliary polarization angle is defined as $\gamma \in [0, \pi/2]$, and the polarization phase difference is given as $\eta \in [-\pi, \pi]$. We omit (n, g) for simplicity. The whole data are divided into M snapshots at each time t_s with sampling frequency f_s according to the Nequist law. Then it picks up enough data r enclosed by each snapshot m with time period $\tau = \dfrac{t_5}{r}$ as short as possible. Then, from (6) each receiving signal measurement value in the mth subspace is given as

$$\boldsymbol{z}^m(\tau) = \boldsymbol{A}s^m(\tau) + \boldsymbol{w}^m(\tau) \tag{13}$$

where $m = 1, 2, \dots, M$. Therefore, the whole space-time steering data matrix can be expressed as

$$\boldsymbol{Z} \stackrel{\text{def}}{=} \begin{bmatrix} z_{1,1}^{1}(0) & \cdots & z_{1,1}^{1}(\tau_1) & \cdots & z_{1,1}^{m}(0) & \cdots & z_{1,1}^{m}(\tau_1) & \cdots & z_{1,1}^{M}(0) & \cdots & z_{1,1}^{M}(\tau_1) \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ z_{I,L}^{1}(0) & \cdots & z_{I,L}^{1}(\tau_1) & \cdots & z_{I,L}^{m}(0) & \cdots & z_{I,L}^{m}(\tau_1) & \cdots & z_{I,L}^{M}(0) & \cdots & z_{I,L}^{M}(\tau_1) \end{bmatrix}. \tag{14}$$

Then

$$\boldsymbol{Z} = [[z^1(\tau)] \quad \cdots \quad [z^m(\tau)] \quad \cdots \quad [z^M(\tau)]] \tag{15}$$

where $\tau_1 = \tau(r-1)$, the dimension of $\boldsymbol{Z}$ for the kth signal is $(2IL \times Mr)$. The mth subspace data matrix can be expressed as

$$\boldsymbol{z}^m(\tau) = \begin{bmatrix} z_{1,1}^{m}(0) & \cdots & z_{1,1}^{m}(\tau_1) \\ \vdots & \ddots & \vdots \\ z_{I,L}^{m}(0) & \cdots & z_{I,L}^{m}(\tau_1) \end{bmatrix}. \tag{16}$$

For the T-ESPRIT scheme, the ESPRIT algorithm is used in an appropriate picked data represented in (14) for each subspace given in (16). It is noted that (15) presents a parallel calculation for each subspace for the same sampling accuracy, then, the calculations load reduction and consequently saving time are achieved.

2.2 T-ESPRIT method for 2-D DOAE

The ESPRIT algorithm is based on a covariance formulation, that is

$$\widehat{\boldsymbol{R}}_{zz} \stackrel{\text{def}}{=} \mathrm{E}[\boldsymbol{Z}(\tau)\boldsymbol{Z}^*(\tau)] = \boldsymbol{A}\widehat{\boldsymbol{R}}_{ss}\boldsymbol{A}^* + \sigma^2\boldsymbol{\Sigma}_W \tag{17}$$

$$\widehat{\boldsymbol{R}}_{ss} = \mathrm{E}[\boldsymbol{S}(\tau)\boldsymbol{S}^*(\tau)] \tag{18}$$

where $\widehat{\boldsymbol{R}}_{zz}$ is the correlation matrix of the sub-array output signal matrix, $\widehat{\boldsymbol{R}}_{ss}$ is the autocorrelation matrix of the signal. The subscript $(*)$ denotes the complex conjugate transpose. The correlation matrix of $\widehat{\boldsymbol{R}}_{zz}$ can be doned for the eigenvalue decomposition as follows:

$$\widehat{\boldsymbol{R}}_{zz} \stackrel{\text{def}}{=} \widehat{\boldsymbol{E}}_S\boldsymbol{\Lambda}\widehat{\boldsymbol{E}}_S^* + \sigma^2\widehat{\boldsymbol{E}}_N\boldsymbol{\Lambda}\widehat{\boldsymbol{E}}_N^* \tag{19}$$

where the eigenvalues are $\lambda_1 > \lambda_2 > \cdots > \lambda_K > \lambda_{K+1} = \cdots = \lambda_{Z(I\times L)} = \sigma^2$.

The eigenvectors $\widehat{\boldsymbol{E}}_S = [\widehat{\theta}_1, \widehat{\theta}_2, \ldots, \widehat{\theta}_K]$ for the larger K eigenvalues span the signal subspace, and the rest $2(I \times L) - K$ smaller eigenvalues $\widehat{\boldsymbol{E}}_N = [\widehat{\theta}_{K+1}, \ldots, \widehat{\theta}_{2(I\times L)}]$ span the noise subspace which is orthogonal to the signal subspace. Therefore, there exists a unique nonsingular matrix $\boldsymbol{Q}$, such that:

$$\widehat{\boldsymbol{E}}_S = \boldsymbol{A}\boldsymbol{Q} = [\boldsymbol{u}_k^{\mathrm{T}} \otimes p_i(\theta_k, \varphi_k) \otimes q_l(\theta_k, \varphi_k)]\boldsymbol{Q}. \tag{20}$$

In (13), $\boldsymbol{A}_{P1}$ and $\boldsymbol{A}_{P2}$ are the first and the last $2L \times (I-1)$ rows of $\boldsymbol{A}$ respectively. The difference between them along the x direction is the factor $\Delta p_k = \mathrm{e}^{\mathrm{j}\frac{2\pi\Delta_x}{\lambda}\sin\theta_k\cos\varphi_k}$. Thus, $\boldsymbol{A}_{P2} = \boldsymbol{A}_{P1}\boldsymbol{\phi}_P$, where $\boldsymbol{\phi}_P$ is the diagonal matrix with diagonal elements Δp_k. Consequently, let $\widehat{\boldsymbol{E}}_{P1}$ and $\widehat{\boldsymbol{E}}_{P2}$ be the first and the last $2L \times (I-1)$ sub-matrices formed from $\widehat{\boldsymbol{E}}_S$. Then the diagonal elements p_k of $\boldsymbol{\phi}_P$ are the eigenvalues of the unique matrix $\boldsymbol{\Psi}_P = \boldsymbol{Q}^{-1}\boldsymbol{\phi}_P\boldsymbol{Q}$, which satisfy

$$\widehat{\boldsymbol{E}}_{P2} = \widehat{\boldsymbol{E}}_{P1}\boldsymbol{\Psi}_P. \tag{21}$$

Similarly, the two $2I \times (L-1)$ sub-matrices $\boldsymbol{A}_{q1}$ and $\boldsymbol{A}_{q2}$ consisting of the rows of $\boldsymbol{A}$ numbered with $2L \times (i-1) + l$ and $2L \times (i-1) + l + 2$ respectively differ by the space factor $\Delta q_k = \mathrm{e}^{\mathrm{j}\frac{2\pi\Delta_y}{\lambda}\sin\theta_k\sin\varphi_k}$ along the y direction, where $l = 1, \ldots, 2(L-1)$. Then $\boldsymbol{A}_{q2} = \boldsymbol{A}_{q1}\boldsymbol{\phi}_q$, where $\boldsymbol{\phi}_q$ is the diagonal matrix with diagonal elements Δq_k.

Consequently, $\widehat{\boldsymbol{E}}_S$ forms the $2I \times (L-1)$ two sub-matrices $\widehat{\boldsymbol{E}}_{q1}$ and $\widehat{\boldsymbol{E}}_{q2}$. Then the diagonal elements Δq_k of $\boldsymbol{\phi}_q$ are the eigenvalues of the unique matrix $\boldsymbol{\Psi}_q = \boldsymbol{Q}^{-1}\boldsymbol{\phi}_q\boldsymbol{Q}$, which satisfies

$$\widehat{\boldsymbol{E}}_{q2} = \widehat{\boldsymbol{E}}_{q1}\boldsymbol{\Psi}_q. \tag{22}$$

It is noted that for multiple signals processing the ordering of the eigenvectors of $\boldsymbol{\Psi}_q$ is generally permuted to the ordering of the eigenvectors of $\boldsymbol{\Psi}_p$. Then, it is essential to pair the eigenvalues of $\boldsymbol{\Psi}_q$ and $\boldsymbol{\Psi}_p$. Thus, for all possible permutations, the eigenvalue of $\boldsymbol{\Psi}_q$ corresponds to Δp_{k_u} the element of the Δq_{k_v} set which realizes

$$\{k_1^0, k_2^0, \ldots, k_K^0\} = \frac{\Delta p_{k_u}}{\Delta q_{k_v}} - \Delta q_{k_t} \tag{23}$$

where $k_u, k_v, k_t = 1, 2, \ldots, K$.

Therefore, it is easy to derivate the arrival angles (θ_k, φ_k) as follows:

$$\theta_k = \arcsin\left\{\frac{\lambda}{2\pi}\left[\left(\frac{\arg(\Delta p_k)}{\Delta_x}\right)^2 + \left(\frac{\arg(\Delta q_k)}{\Delta_y}\right)^2\right]^{1/2}\right\} \tag{24}$$

$$\varphi_k = \arctan\left[\frac{\Delta_x}{\Delta_y}\cdot\frac{\arg(q_k)}{\arg(p_k)}\right]. \tag{25}$$

2.3 Optimal DOAE calculation

The sub-planar pair is shown in Fig. 3.

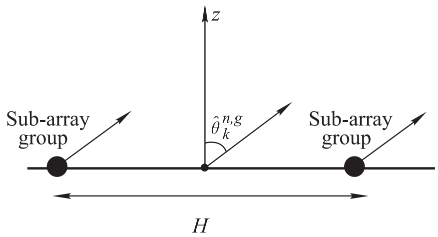

Fig. 3 Arrangement of sub-planar pair

The TDOA (δ^{ng}) for the kth received signal is calculated [20] as follows:

$$\delta_k^{n,g} = \frac{H}{c}\sin\widehat{\theta}_k^{n,g} \tag{26}$$

where c is the wave velocity (3×10^8 m/s) and H is the distance between any (n,g) sub-array groups as shown in Fig. 3. For the sub-planar groups shown in Fig. 4, the TDOA between group $(1,1)$ and group (N,G) for the kth source is denoted by δ_k^{1G}, and the TDOA between group $(N,1)$ and group $(1,G)$ for the kth source is denoted by $\delta_k^{N,1}$.

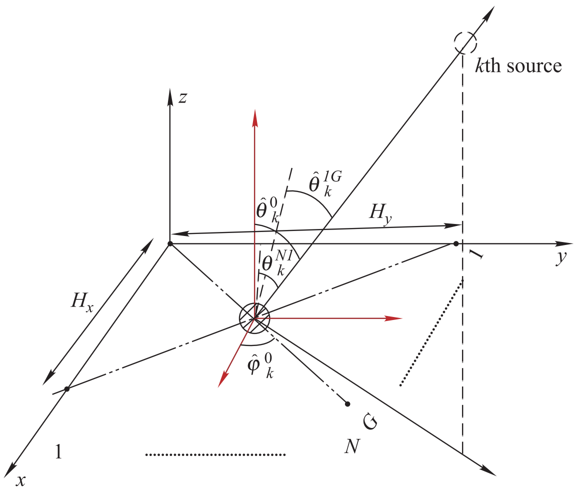

Fig. 4 Arrangement of sub-planar groups

Then, from (26) we have

$$\delta_k^{1,G} = \frac{H}{c}\sin\widehat{\theta}_k^{1,G} \tag{27}$$

$$\delta_k^{N,1} = \frac{H}{c}\sin\widehat{\theta}_k^{N,1} \tag{28}$$

$$H = \sqrt{(H_x)^2 + (H_y)^2} \tag{29}$$

where H_x and H_y are the distance between the first and last sub-array arranged along x and y directions respectively.

$$H_x = x_c^{g=G} - x_c^{g=1} \tag{30}$$

$$H_y = y_c^{n=N} - y_c^{n=1} \tag{31}$$

where x_c^g is the coordinate of the (g) sub-array center point, and y_c^n is the coordinate of the (n) sub-array center point with respect to the reference point along x and y directions respectively.

Thus, (3) and (5) could be modified to represent the coordinates of any (n,g) sub-array with respect to the reference point as follows:

$$x_c^g = \left(\frac{(I-1)}{2}\Delta_x\right) + ((g-1)I\Delta_x) \tag{32}$$

$$x_c^n = \left(\frac{(L-1)}{2}\Delta_y\right) + ((n-1)L\Delta_y) \tag{33}$$

$$\widehat{\theta}_k^{1,G} = \frac{\widehat{\theta}_k^{1,1} + \widehat{\theta}_k^{N,C}}{2} \tag{34}$$

$$\widehat{\theta}_k^{N,1} = \frac{\widehat{\theta}_k^{N,1} + \widehat{\theta}_k^{N,C}}{2} \tag{35}$$

where the value of θ_k for any (n,g) sub-array group is estimated as in (24). Substituting (29)–(35) into (27) and (28), the kth received signal TDOA ($\delta_k^{1G}, \delta_k^{N1}$) is obtained. As shown in Fig. 4, the optimal DOAE values (θ_k^0, φ_k^0) are measured at the center of the sub-array groups which are located in the cross point of the straight lines passing through group $(1,1)$ and group (N,G) and through group $(N,1)$ and group $(1,G)$. Thus, (θ_k^0, φ_k^0) values can be represented [20–22] in terms of ($\widehat{\theta}_k^{1,G}, \widehat{\theta}_k^{N,1}$) as follows:

$$\sin\widehat{\theta}_k^{1,G} = \sin\widehat{\theta}_k^0 \sin\widehat{\varphi}_k^0 = \frac{c\delta^{1,G}}{H} \tag{36}$$

$$\sin\widehat{\theta}_k^{N,1} = \sin\widehat{\theta}_k^0 \cos\widehat{\varphi}_k^0 = \frac{c\delta^{N,1}}{H}. \tag{37}$$

From (36) and (37), the optimal DOAE values are expressed as

$$\widehat{\varphi}_k^0 = \arctan\left(\frac{\delta_k^{1,G}}{\delta_k^{N,1}}\right) \tag{38}$$

$$\widehat{\theta}_k^0 = \arcsin\left(\frac{c}{H}\sqrt{(\delta_k^{1,G})^2 + (\delta_k^{N,1})^2}\right). \tag{39}$$

3. Simulation results

Considering the 2D-DOAE process with AWGN, the parameters are given as $f_s = 25$ MHz. Assume total temporal snapshots are 25, pickup the enclosed data 20 times, and do 200 independent Monte Carlo simulations. In order to validate the proposed method, it has been used in the planar case with number of elements, such as $(I,L) = (3,3)$, $(N,G) = (2,2)$ with displacement values $\Delta_x = \Delta_y = \lambda/2$, with initial values $\theta = 45°$ and $\varphi = 60°$.

Fig. 5 presents the RMSEs of the T-ESPRIT algorithm applied on array with elements (6,6) without dividing to sub-arrays, and the RMSEs of the proposed algorithm

(T-ESPRIT with spatial subspace) by dividing the planar array into two sub-planar arrays with $(I, L) = (3, 3)$, $(N, G) = (2, 2)$.

Fig. 5 indicates that the proposed algorithm errors are getting closer to the CRB as a result of applying spatial subspace concept which enables multiple phase deference measurements with different resolutions with respect to the same reference point.

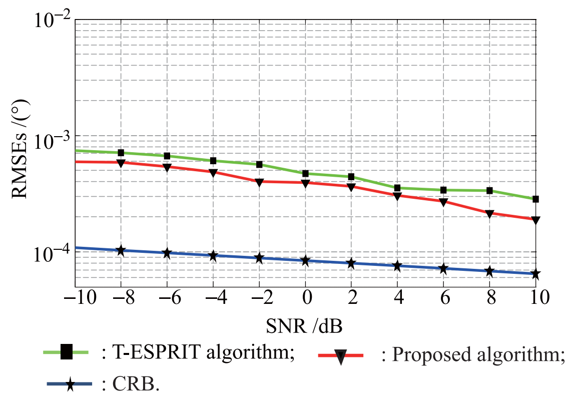

Fig. 5 RMSEs vs. SNR for T-ESPRIT algorithm and the proposed algorithm

Comparison results displayed in Fig. 6 show that errors of the proposed algorithm are less than that of the 2D Beam ESPRIT, the ESPRIT-Like, and the Quaternion ESPRIT algorithms used in [13–15] respectively, especially at the low SNR. This upgrade has been realized due to two factors. The first factor is the applying of the time subspace approach which decreases the errors caused by the model non-linearity effect. And the second factor is the using of spatial subspace technique which increases the resolution of phase deference measurement.

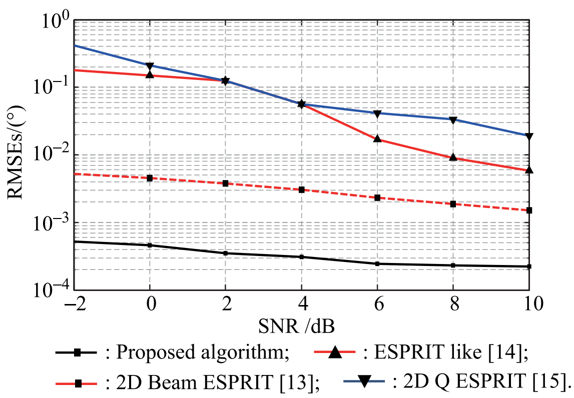

Fig. 6 RMSEs vs. SNR for the proposed algorithm and ESPRIT methods

Table 1 represents the computational time and complexity.

Table 1 Computation time and complexity

Method	Computation	
	Time/ms	Complexity
Conventional ESPRIT	17.7	$O([4d(IGLN)^2 + 8(IGLN)^3])$
Proposed algorithm	1.14	$O([M + 4r(IL)^2 + 8(IL)^3])$

From Table 1, it has been found that the proposed algorithm requires $O([M + 4r(IL)^2 + 8(IL)^3])$ flops, while the conventional ESPRIT needs $O([4d(IGLN)^2 + 8(IGLN)^3])$ flops. The proposed algorithm requires only about 6% computational time of the conventional ESPRIT as a result of using the TDOA method.

We can figure out that the combination between the T-ESPRIT algorithm and the spatial subspace algorithm using TDOA technique, which forms the proposed improved TS-ESPRIT algorithm, has achieved success in improving the DOAE accuracy with low computational load. Simply, the proposed method improves the estimation performance.

4. Conclusions

In this paper, a new ESPRIT method is developed based on the concept of subspace. Firstly, the T-ESPRIT method is used to estimate DOA for each sub-array to realize the time subspace concept. Secondly, the T-ESPRIT method is combined with the TDOA algorithm to compute the optimal DOAE value in order to realize the temporal-spatial subspace concept. It has been found that the estimation accuracy has been improved with low computational load. The computational time has been reduced by about 94%, which consequently enhances the estimation performance.

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