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DOA error estimation in 3D cylindrical dipole array geometries including the mutual coupling effect

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A B S T R A C T

The direction of arrival (DOA) error in dipole 3D arrays is estimated through Monte-Carlo simulations using the standard MUSIC algorithm. Novel 3D geometries are implemented which demonstrate better precision given the same lateral area. The mutual coupling effect is included by changing the search vector in the MUSIC DOA algorithm for the novel 3D geometries. A simple straight forward method is used which does not need complex electromagnetic computations. Simulations show that the proposed method can successfully account for the mutual coupling effects in two dimensional direction finding (both azimuth and elevation angle) with novel 3D array geometries. Reduced DOA estimation error is observed in the novel geometries which can be used as a method of mitigation for the mutual coupling effect.

1. Introduction

In the past decades different DOA estimation algorithms have been evaluated and examined for 1-D and 2-D smart antenna arrays. Some of these algorithms such as MUSIC and ESPRIT showed accurate and stable performances in azimuth or azimuth/elevation estimations with different numbers of snapshots and SNR values [1]. In practical cases where the mutual coupling between antenna elements or scattering effects of the environment are significant, most DOA estimation algorithms failed to predict the angle of arrival for numerous sources correctly. Different studies were conducted to compute the effect of mutual coupling on the DOA estimation algorithms. In one of the initial studies in [2] the authors considered the effect of mutual coupling on the performance of adaptive arrays and used a deterministic solution to obtain the steering vector required to maximize the output SINR (Signal to Interference and Noise Ratio). In [3] the effect of mutual coupling in the linear arrays with 1-D (elevation only) MUSIC direction finding method was eliminated by changing the search vector. In [4] the authors developed an eigenstructure based algorithm for direction finding and calibration of the array parameters. In [5] the mutual coupling effect was considered by an electromagnetic computation method for both Bartlett and MUSIC direction of arrival estimations. In [6] authors used the method of [5] for MUSIC direction of arrival estimation with circular array configuration. Another comparative study between the performance of MUSIC and Bartlett DOA estimations which considered the mutual coupling effects of physical dipole antenna arrays with impedance matrix was conducted in [7] and the authors showed that the MUSIC direction finding has a more accurate angular estimation than the Bartlett algorithm. In [8] Method of Moment (MoM) was used to characterize the antenna array for considering the mutual coupling effect. In [9] a new method for the calculation of mutual impedances based on an estimated current distribution was introduced. In [10] a blind calibration method was used for the mutual coupling effect and DOA estimation and it showed that the Uniform Circular Array (UCA) has some advantages compared to Uniform Linear Array (ULA) in wideband applications.

As mentioned above many different methods were proposed for 1-D (elevation only) direction of arrival estimations in the presence of mutual coupling between elements of the array. Most of these solutions were based on the ULA or UCA or URA (Uniform Rectangular Array) configurations of antennas for azimuth or elevation estimation. Some methods were introduced for both azimuth and elevation estimations in [11–13]. Effect of mutual coupling on the 2-D (azimuth and elevation) MUSIC algorithm with MoM matrix method was compensated in [11]. Combining the uniform circular array-RAnk REduction (UCA-RARE) and Root-MUSIC algorithm for 2-D (azimuth and elevation) direction of arrival (DOA) estimation for uniform circular arrays in the presence of mutual coupling was examined in [12]. In [13] the authors used auxiliary sensors on the boundary of Uniform Rectangular Array (URA) to estimate accurate DOA for elevation and azimuth angles and mutual coupling without any calibration or iterative procedure. In [14] a Modified Root-MUSIC algorithm is proposed to estimate the angle of arrival and the polarization of the plane waves with diversely polarized uniform circular array (UCA) in the presence of mutual coupling effects

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between the antenna arrays. Another algorithm which modifies the beam space for 2D DOA estimation in the presence of mutual coupling effect, with a small number of elements in UCA configuration was proposed in [15]. Improving the accuracy of both azimuth and elevation angles estimation in the presence of mutual coupling is still an open area for the researchers. Considering the mutual coupling effect between the elements of 3D antenna geometries employing 2-D (azimuth and elevation) MUSIC direction finding algorithm is a new issue for DOA estimations. In this paper we employ the basic formulation of [3] which is based on the MUSIC direction finding algorithm for compensation of mutual coupling effects between the elements of the arrays for a number of 3D array geometries, namely 3D circular array, 3D triangular array and 3D rotated circular array and 3D rotated triangular array of half-wave dipole antennas for joint azimuth and elevation angles estimation. These novel geometries were introduced in [16] and Monte-Carlo simulations showed that the rotated cross section 3D arrays demonstrated lower error estimation than the normal 3D arrays without accounting for the mutual coupling effect. We employ some of these novel geometries with two-layer and three-layer configurations using the direction finding MUSIC algorithm with mutual coupling effect included, to achieve a more realistic error estimation.

Incident signals are assumed to be uncorrelated sources and Monte-Carlo simulations are conducted to compare the RMSE (Root Mean Square Error) of the arrival angles for different configurations. This study investigates the effect of array geometry (2D and 3D arrays) on the accuracy of azimuth and elevation angles estimation in presence of mutual coupling effects based on the extension of the method used in [3]. It has been demonstrated that with this approach MUSIC algorithm can be utilized for both azimuth and elevation angles estimation with sufficient accuracy in presence of mutual coupling among the elements. Monte-Carlo simulation shows that the proposed method for azimuth and elevation angles estimation with 3D array configuration achieves a good resolution in comparison to other geometries [16]. This method does not need the complex time consuming numerical electromagnetic computations. Furthermore the introduction of the new rotated array geometries including two-layer and three-layer triangular arrays provide better resolution in comparison to the conventional arrays, in the presence of mutual coupling.

This paper is divided into four sections. Section 2 presents the data model for proposed arrays in presence of mutual coupling effect between dipole antennas. Section 3 represents the comparison of 3D circular and 3D triangular geometries' performances with equal lateral areas using physical dipole elements. Finally Section 4 draws the conclusion.

2. Data model for proposed arrays in presence of mutual coupling

Two dimensional arrays such as circular arrays can estimate azimuth angles with a high resolution while they have less accuracy in estimating elevation angles with respect to three dimensional arrays. For this reason the three dimensional arrays are proposed. Typical three dimensional cylindrical arrays like 3D circular and 3D triangular with 36 elements are shown in Fig. 1a and b. These arrays contain isotropic elements. So the radiation pattern can be described by the array factor. In order to obtain the array model and estimate the azimuth/elevation angles of arrival by MUSIC algorithm, the first step is to find the array steering vector $\boldsymbol{a}(\theta, \varphi)$ for isotropic elements [16].

$$\boldsymbol{a}(\theta,\varphi) = e^{-j\boldsymbol{PK}} \tag{1}$$

where $\boldsymbol{P}$ is the position matrix of array elements and $\boldsymbol{K}$ is the wave number matrix.

In this study, three dimensional arrays contain M planes of circular or triangular arrays and each array consists of N elements. So the wave number matrix is defined by:

$$\boldsymbol{K} = [\boldsymbol{k}_C\ \boldsymbol{k}_C\ \dots\ \boldsymbol{k}_C]^T_{(3M)\times 1} \tag{2}$$

where $\boldsymbol{k}_C$ is the wave vector and T superscript stands for transpose matrix.

$$\boldsymbol{k}_C = \frac{2\pi}{\lambda}[\sin\theta\cos\varphi\ \sin\theta\sin\varphi\ \cos\theta] \tag{3}$$

where λ is the operating wave-length and the position matrix of the array elements is given by:

$$\boldsymbol{P} = [\boldsymbol{r}_x\ \boldsymbol{r}_y\ \boldsymbol{z}_1,\ \boldsymbol{r}_x\ \boldsymbol{r}_y\ \boldsymbol{z}_2,\ \dots,\ \boldsymbol{r}_x\ \boldsymbol{r}_y\ \boldsymbol{z}_M]_{N\times(3M)} \tag{4}$$

where $\boldsymbol{r}_x$, $\boldsymbol{r}_y$ and $\boldsymbol{z}_m$ are the position of mth circular array elements on x-axis, y-axis and z-axis respectively. For example, in the circular configuration case which is centered at the origin the position of elements are given as below.

$$\boldsymbol{r}_x = R[\cos\varphi_1\ \cos\varphi_2\ \dots\ \cos\varphi_N]^T_{N\times 1} \tag{5}$$

$$\boldsymbol{r}_y = R[\sin\varphi_1\ \sin\varphi_2\ \dots\ \sin\varphi_N]^T_{N\times 1} \tag{6}$$

$$\boldsymbol{z}_m = h_m[1\ 1\ \dots\ 1]^T_{N\times 1} \tag{7}$$

In the above equations, R is the radius of each circular array, $\varphi_n = \frac{2\pi}{N}(n-1), n = 1,2,\dots,N$ and () is the height of the mth plane. By substituting Eqs. (5)–(7) in (4), the position matrix ($\boldsymbol{P}$) in circular configuration can be written as:

$$\boldsymbol{P} = \begin{bmatrix} R\cos\varphi_1 & R\sin\varphi_1 & h_1 & R\cos\varphi_1 & R\sin\varphi_1 & h_2 & & R\cos\varphi_1 & R\sin\varphi_1 & h_M \\ R\cos\varphi_2 & R\sin\varphi_2 & h_1 & R\cos\varphi_2 & R\sin\varphi_2 & h_2 & & R\cos\varphi_2 & R\sin\varphi_2 & h_M \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \dots & \vdots & \vdots & \vdots \\ R\cos\varphi_N & R\sin\varphi_N & h_1 & R\cos\varphi_N & R\sin\varphi_N & h_2 & & R\cos\varphi_N & R\sin\varphi_N & h_M \end{bmatrix}_{N\times(3M)} \tag{8}$$

So the array steering vector is obtained as,

$$\boldsymbol{a}(\theta,\varphi) = \begin{bmatrix} e^{j\frac{2\pi}{\lambda}[MR\sin\theta\cos(\varphi-\varphi_1)+(h_1+h_2+\dots+h_M)\cos\theta]} \\ e^{j\frac{2\pi}{\lambda}[MR\sin\theta\cos(\varphi-\varphi_2)+(h_1+h_2+\dots+h_M)\cos\theta]} \\ \vdots \\ e^{j\frac{2\pi}{\lambda}[MR\sin\theta\cos(\varphi-\varphi_N)+(h_1+h_2+\dots+h_M)\cos\theta]} \end{bmatrix}_{N\times 1} \tag{9}$$

For the triangular configuration one can compute $\boldsymbol{r}_x$, $\boldsymbol{r}_y$ and z_m of mth element of triangular array in the cartesian coordinates system and replace it as the position vector in Eqs. (7)–(9) respectively. If the process $\boldsymbol{x}$ is ergodic, the array correlation matrix can be computed by Eq. (10).

$$\boldsymbol{R}_{xx} \approx \frac{1}{K}\sum_{k=1}^{K}\boldsymbol{x}(k)\boldsymbol{x}^H \tag{10}$$

Where H superscript stands for the Hermitian vector and

$$\boldsymbol{x}(k) = [\boldsymbol{a}(\theta_1,\varphi_1),\ \boldsymbol{a}(\theta_2,\varphi_2),\ \dots,\ \boldsymbol{a}(\theta_D,\varphi_D)]\begin{bmatrix} s_1(k) \\ s_2(k) \\ \vdots \\ s_D(k) \end{bmatrix} + \boldsymbol{n}(k) = \boldsymbol{A}\boldsymbol{s}(k) + \boldsymbol{n}(k) \tag{11}$$

In (11), $\mathbf{A}$ is the matrix of steering vectors, $\boldsymbol{s}(k)$ is the vector of incident signals at the kth snapshot, $\boldsymbol{n}(k)$ is the noise vector at the kth snapshot and D is the number of incident signals. So the MUSIC pseudospectrum is obtained as [1],

$$P_{MUSIC}(\theta,\varphi) = \frac{1}{|[\boldsymbol{a}^H(\theta,\varphi)\boldsymbol{E}_n\boldsymbol{E}_n^H\boldsymbol{a}(\theta,\varphi)]|} \tag{12}$$

where $\boldsymbol{E}_n$ is the noise subspace of the array correlation matrix. Eqs. (10)–(12) present the MUSIC pseudospectrum in the ideal situation with arrays of isotropic elements. As a realistic situation, we use half-wave dipole antennas in the array structures and consider the mutual coupling between antennas by expanding the method employed in [3] for two-plane and three-plane of circular and triangular arrays and their corresponding rotated cross section counterparts when the incident signals are uncorrelated.