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Calibration of directional mutual coupling for antenna arrays

Ahmet M. Elbir

Dept. of Electrical and Electronics Engineering, Duzce University, 81620, Duzce, Turkey

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ABSTRACT

Mutual coupling (MC) is one of the major error sources in array signal processing. The previous methods mostly assume that the MC is direction-independent and it is modeled by a single MC matrix. However, this is not valid in a practical scenario where the effect of MC differs for the source signals incoming from different directions. In this paper, calibration of directional MC is considered for direction-of-arrival (DOA) estimation problem. An alternating and sectorized parameter estimation (ASPE) algorithm is proposed where the estimates of the source DOA angles and the MC coefficients corresponding to each source direction are found iteratively. A unified approach is introduced so that the proposed algorithm can effectively work for different array geometries regardless of the array geometry and the corresponding MC matrix model. The performance of the proposed method is evaluated by several experiments and it is compared with the conventional calibration techniques as well as the Cramer–Rao lower Bound which is derived for the considered problem. It is shown that the proposed method effectively finds the unknown source and coupling parameters and it has superior performance as compared to the conventional calibration techniques.

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1. Introduction

Direction-of-arrival (DOA) estimation of unknown source locations is an important topic in array signal processing as well as in radar, sonar and communications [1]. While there are several methods proposed for this purpose such as the MUSIC (MUltiple SIgnal Classification) algorithm [2], most of them require the exact knowledge of the array manifold. In a practical scenario, the antennas in the array have mutual coupling (MC) which corrupts the array data and degrades the DOA estimation performance significantly [3].

Several methods are proposed for the estimation of source DOA angles in the presence of MC [4–19]. In [4–7], joint DOA angle and MC coefficient estimation problem is considered for uniform linear arrays (ULA). In [8,9] and [10], recursive rank reduction methods are used for MC calibration for ULA and uniform circular array (UCA). In [11], an alternating minimization algorithm is proposed for the compensation of MC for ULA. Higher order statistics are used in [12] and [13] for DOA estimation problem in the presence of MC. In [13–15], random array structures are considered for the same problem. [16] studies the problem of single snapshot DOA estimation in the presence of MC for a UCA. In [17] and [18], DOA estimation problem is considered in the presence of MC and multipath. An alternating direction based method is proposed in [19] using the sparsity of the source DOA angles in the spatial domain. Notice that, the above methods are based on the assumption that the MC among the antennas is direction-independent. In this case, MC is modeled by a single MC matrix in the array model [20] and it is the same for all source directions. However in practice, antennas have non-omnidirectional beampattern so that the array response differs both in gain and phase for each source direction [21] and MC becomes direction-dependent. Therefore, directional-dependency of MC should be taken into account for a realistic scenario and accurate estimation performance.

There are limited number of works which consider the effect of direction-dependent MC on DOA estimation problem [22–24]. In [22], a sectorized approach is proposed for the estimation of source DOA angles using patch antennas which have non-omnidirectional beampattern. [22] uses the assumption that the effect of MC does not change in certain angular sectors. [23] uses a similar approach by employing multiple known calibration matrices for MC. In [24], a rank reduction based method is proposed for a UCA in the presence of elevation-dependent MC where the MC matrix is estimated by the receiving-mutual-impedance method proposed in [25,26]. While these methods provide sufficient direction finding (DF) accuracy, they require the knowledge of the MC matrix to be known or estimated by an offline technique before the DF operation. This issue poses an accuracy problem since the estimated parameters of an offline calibration technique cannot accurately represent the system dynamics for a long period of time [27]. This is an im-

E-mail addresses: ahmetmelbir@gmail.com, ahmetelbir@duzce.edu.tr.

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portant problem especially when the system parameters change in time [3].

In the context of DOA estimation under unknown MC, most of the methods are proposed for certain array structures [4–9,11,12, 17–19]. These methods are based on the special structure of the MC matrix such as Toeplitz, circulant and block-Toeplitz. Therefore, the construction of the MC matrix differs for different array geometries such as for ULA, UCA [3, See Lemma 2 and 3] and URA [28]. This paper addresses this problem and proposes a novel approach so that the construction of the MC matrix does not depend on the array geometry.

In order to mitigate the effect of MC, an "array shrinkage" approach is used in [4] and [29–31]. While this approach provides a non-iterative solution for parameter estimation, it causes an aperture loss in the array so that the DF accuracy is significantly reduced. In order to eliminate this loss, a transformation-based approach is proposed in [28] in the presence of direction-independent MC. This method also fails in case of directional MC.

In this paper, calibration of the antenna arrays for DOA estimation in the presence of directional MC is considered. An alternating and sectorized parameter estimation (ASPE) algorithm is proposed for the joint estimation of DOA angles of the unknown source locations and MC coefficients. The proposed method finds the DOA angle of the sources by using the MUSIC algorithm [2]. The estimation of the MC coefficients is done in an optimum manner by solving a linearly constrained quadratic minimization problem. The angular space is divided into small sectors where the effect of MC is assumed to be the same. Then the MUSIC spectrum is obtained for each angular sector for the DOA estimation. The performance of the proposed calibration technique is compared with both conventional methods and the Cramer–Rao lower bound (CRB) which is derived at the end of the paper for the considered problem.

2. Array model and problem formulation

In this paper, estimation of DOA angles of K narrowband source signals impinging on an M-element antenna array is considered. In traditional works [4–9,11–19] where the direction-independent MC is assumed, the array output is given as follows

$$\mathbf{y}(t_i) = \mathbf{C}\mathbf{A}\mathbf{s}(t_i) + \mathbf{w}(t_i), \quad i = 1, \dots, T \tag{1}$$

where T is the number of snapshots, $\mathbf{w}(t_i)$ is spatially and temporarily white Gaussian noise vector and $\mathbf{s}(t_i) = [s_1(t_i), s_2(t_i), \dots, s_K(t_i)]^T$ is a $K \times 1$ vector composed of the source signals. $\mathbf{A} = [\mathbf{a}_1, \mathbf{a}_2, \dots, \mathbf{a}_K]$ is the $M \times K$ array steering matrix and the mth element of $\mathbf{a}_k$ is given as

$$a_{mk} = \exp\{j \frac{2\pi \mathbf{p}_m^T \mathbf{r}_k}{\lambda}\} \tag{2}$$

where λ is the wavelength and $\mathbf{p}_m = [x_m, y_m, z_m]^T$ is the position of the mth antenna in Cartesian coordinate system and $\mathbf{r}_k = [\cos(\phi_k)\sin(\varphi_k), \sin(\phi_k)\sin(\varphi_k), \cos(\varphi_k)]^T$. ϕ_k and φ_k denote the azimuth and the elevation angle of the kth source direction respectively.

In case of directional MC, the array output can be modeled as

$$\mathbf{y}(t_i) = \sum_{k=1}^{K} \mathbf{C}_k \mathbf{a}_k s_k(t_i) + \mathbf{w}(t_i), \quad i = 1, \dots, T \tag{3}$$

which can be written in a compact form as

$$\mathbf{y}(t_i) = \tilde{\mathbf{A}}\mathbf{s}(t_i) + \mathbf{w}(t_i), \quad i = 1, \dots, T \tag{4}$$

where

$$\tilde{\mathbf{A}} = [\mathbf{C}_1\mathbf{a}_1, \mathbf{C}_2\mathbf{a}_2, \dots, \mathbf{C}_K\mathbf{a}_K]. \tag{5}$$

$\mathbf{C}_k$ denotes the MC matrix corresponding to the kth source direction (ϕ_k, φ_k). In other words, the coupling contribution of each source signal to is different for $k = 1, \dots, K$.

The aim of this work is to estimate the unknown source DOA angles and the MC matrices $\{\phi_k, \varphi_k, \mathbf{C}_k\}_{k=1}^K$ given the array output $\{\mathbf{y}(t_i)\}_{i=1}^T$ and antenna positions $\{\mathbf{p}_m\}_{m=1}^M$.

3. The structure of the MC matrix

The structure of the MC matrix differs for different array geometries. In this section, the MC structures of commonly used antenna arrays such as ULA, UCA and URA are given. The structures of the MC matrix of a ULA and UCA are given as [3]

$$\mathbf{C}^{\text{ULA}} = \text{Toeplitz}\{[c_1, c_2, \dots, c_M]\}. \tag{6}$$

$$\mathbf{C}^{\text{UCA}} = \begin{cases} M \text{ is even}, \\ \text{Toeplitz}\{[c_1, c_2, \dots, c_L, c_{L-1}, \dots, c_2]\}. \\ M \text{ is odd}, \\ \text{Toeplitz}\{[c_1, c_2, \dots, c_L, c_L, c_{L-1}, \dots, c_2]\} \end{cases} \tag{7}$$

where $\{c_l\}_{l=1}^L$ are the distinct MC coefficients. The structure of the MC matrix for an $M \times \bar{M}$ URA can be given as follows [30]

$$\mathbf{C}^{\text{URA}} = \begin{pmatrix} \tilde{\mathbf{C}}_1 & \tilde{\mathbf{C}}_2 & \dots & \tilde{\mathbf{C}}_{M-1} & \tilde{\mathbf{C}}_M \\ \tilde{\mathbf{C}}_2 & \tilde{\mathbf{C}}_1 & \tilde{\mathbf{C}}_2 & \dots & \tilde{\mathbf{C}}_{M-1} \\ \vdots & \tilde{\mathbf{C}}_2 & \ddots & \ddots & \vdots \\ \tilde{\mathbf{C}}_{M-1} & \ddots & \ddots & \tilde{\mathbf{C}}_1 & \tilde{\mathbf{C}}_2 \\ \tilde{\mathbf{C}}_M & \tilde{\mathbf{C}}_{M-1} & \dots & \tilde{\mathbf{C}}_2 & \tilde{\mathbf{C}}_1 \end{pmatrix}. \tag{8}$$

$\tilde{\mathbf{C}}_m$ is an $\bar{M} \times \bar{M}$ MC matrix corresponding to the mth subarray and

$$\tilde{\mathbf{C}}_m = \text{Toeplitz}\{[c_1^{(m)}, c_2^{(m)}, \dots, c_{\bar{M}}^{(m)}]\} \tag{9}$$

where $c_{\bar{m}}^{(m)}$ is the coupling coefficient in the mth subarray.

Hence the number of distinct MC coefficients for the above arrays can be given as

$$L = \begin{cases} M, & \text{ULA} \\ \frac{M}{2} + 1, & \text{UCA with } M \text{ is even} \\ \frac{M+1}{2}, & \text{UCA with } M \text{ is odd} \\ M\bar{M}, & \text{URA} \end{cases}. \tag{10}$$

4. Estimation of DOA angles

In this section, the estimation of the unknown source DOA angles is investigated. First, we define the array covariance matrix as

$$\hat{\mathbf{R}}_y = \frac{1}{T}\sum_{i=1}^{T} \mathbf{y}(t_i)\mathbf{y}^H(t_i) = \tilde{\mathbf{A}}\hat{\mathbf{R}}_s\tilde{\mathbf{A}}^H + \hat{\mathbf{R}}_w \tag{11}$$

where $\hat{\mathbf{R}}_s$ and $\hat{\mathbf{R}}_w$ are signal and noise sample covariance matrices respectively. Using eigendecomposition, $\hat{\mathbf{R}}_y$ can be written as

$$\hat{\mathbf{R}}_y = \mathbf{U}\mathbf{\Lambda}\mathbf{U}^H \tag{12}$$

where $\mathbf{\Lambda} = \text{diag}(\sigma_1, \sigma_2, \dots, \sigma_M)$ is a diagonal matrix composed of the eigenvalues of $\hat{\mathbf{R}}_y$ in a descending order. $\mathbf{U} = [\mathbf{U}_s \; \mathbf{U}_n]$ represents the signal and noise subspace eigenvector matrices respectively ($\mathbf{U}_s \in \mathbb{C}^{M \times K}$ and $\mathbf{U}_n \in \mathbb{C}^{M \times M-K}$). Due to the orthogonality of signal and noise subspaces, $\mathbf{U}_s \perp \mathbf{U}_n$ holds [2]. Furthermore, the columns of $\mathbf{U}_s$ and $\tilde{\mathbf{A}}$ span the same space. Then we can write the following property, i.e.

$$||\mathbf{U}_n^H \tilde{\mathbf{A}}||_F^2 = 0. \tag{13}$$

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