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Localization of mixed far-field and near-field sources under unknown mutual coupling

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ABSTRACT

In this paper, a novel localization algorithm for mixed far-field and near-field sources is proposed in the presence of unknown mutual coupling. Based on the principle of rank reduction, direction-of-arrival (DOA) estimates of far-field sources are firstly decoupled under unknown mutual coupling. Then these estimates are employed to generate the mutual coupling coefficients. Finally, by the mutual coupling compensation and the far-field components elimination, near-field sources parameters (DOA and range) are obtained. The proposed algorithm is efficient in that it only requires second order statistics and one dimensional spectral search. Simulation results demonstrate that our algorithm is effective for the classification and localization of mixed sources under unknown mutual coupling.

1. Introduction

Source localization using sensor array techniques have received considerable attention over the past decades. Most of the existing algorithms concentrate on far-field (FF) radiating sources, whose wavefronts are plane waves. Many high resolution algorithms have been proposed for the direction-of-arrival (DOA) estimation under the FF assumption, such as multiple signal classification (MUSIC) method [1], the estimation of signal parameters via rotational invariance technique (ESPRIT) [2], and their derivatives [3,4]. These algorithms are generally based on the assumption of ideal array manifold which does not take the manifold mismatch into account, such as spherical wavefronts [5] and mutual coupling [6].

However, in many situations of interest, the radiating sources may lie in the near-field (NF) region of the array [7], where the wavefronts are spherical and both the DOA and the range parameters are needed to localize these sources [5]. Consequently, traditional FF DOA estimation algorithms would produce unreliable results for NF source localization. Fortunately, a bunch of NF source localization algorithms have been developed in recent years, including the 2-D MUSIC algorithm [5], the covariance approximation (CA) method [8,9], the weighted linear prediction method [10], and the rank-reduction (RARE) type algorithms [11–15]. Moreover, both FF and NF sources may coexist in many practical applications, such as electronic surveillance, seismic exploration and speaker localization using microphone arrays. Most of the algorithms, which deal with pure NF or pure FF sources, may fail in the scenarios of mixed sources.

In recent years, a lot of algorithms have been developed for mixed source localization [16–22]. In [16], Liang et al. proposed a two-stage MUSIC (TSMUSIC) method, which is based on fourth-order cumulant (FOC). However, TSMUSIC requires high computational load to construct cumulant matrices. In [17], a second-order-statistics-based oblique projection MUSIC (OPMUSIC) algorithm is presented. Although this method is computationally efficient, it suffers from severe array aperture loss. Based on the generalized ESPRIT (GESPRIT) algorithm [11], Liu and Sun presented a GESPRIT-like algorithm to alleviate the aperture loss and obtain a reasonable classification result [20]. But its FF component elimination technique would bring extra estimation errors.

It is well-known that the mutual coupling effect between two elements is inversely proportional to their distance [6]. Unfortunately, in all of the abovementioned mixed source localization algorithms, the inter-sensor spacing is constrained to be within ***a quarter wavelength***. In this scenario, the mutual coupling effect should no longer be ignored. Otherwise, without calibration, the performance of these algorithms might degrade substantially. Many mutual coupling models and corresponding DOA estimation algorithms have been presented with the FF assumption [6,23–28]. In [6], an iterative method is advanced to compensate both the mutual coupling effect and the gain and phase errors. However, it needs an initial estimate of the manifold perturbations. Based on the concept of auxiliary sensors, various middle subarray methods

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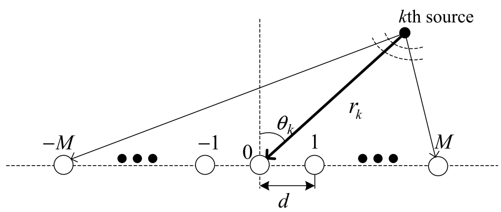

Fig. 1. Symmetric ULA configuration for the proposed algorithm.

are adopted to estimate DOAs [23,24]. Although these methods require neither calibration sources nor iterations, they suffer from array aperture loss caused by setting auxiliary sensors. In [25], a FOC-based algorithm is presented to alleviate this aperture loss problem. Another important type of methods for DOA estimation under mutual coupling is based on RARE [26–28]. The main advantage of these methods is that the whole array aperture is fully utilized. Therefore, they are expected to offer a better estimation performance. Even though these algorithms are effective under the FF assumption, little attention has been paid for the mixed FF and NF localization problem.

In view of the previous analyses, most existing algorithms are faced with the following difficulties: 1) being able to localize mixed sources successfully under unknown mutual coupling; 2) reasonable classification of FF and NF sources; 3) avoiding multidimensional search and high order statistics; 4) avoiding parameter matching.

Aiming to solve these difficulties, we propose a novel Two Stage RARE (TSRARE) algorithm in this paper to localize mixed FF and NF sources with unknown mutual coupling effect. Based on the symmetric Toeplitz structure of the mutual coupling matrix (MCM), a RARE estimator is firstly formed to obtain the FF DOA estimates, which successfully decouple the multi-dimensional spectral search into a one-dimensional (1D) search. After mutual coupling compensation, another covariance differencing RARE estimator is constructed to generate the NF DOA estimates, which is effective to eliminate the FF components. The Cramer–Rao bounds (CRBs) for this problem are also derived to evaluate the performance of the proposed algorithm.

The rest of this paper is organized as follows. In Section 2, the mixed FF and NF signal model under unknown mutual coupling is presented. The proposed method is described in Section 3. In Section 4, simulations are conducted to validate the performance of our method. We conclude this paper in Section 5. Finally, the CRBs are obtained in Appendix.

Throughout the paper, the complex conjugate, transpose, Hermitian transpose, pseudo-inverse are denoted by $(\cdot)^*$, $(\cdot)^T$, $(\cdot)^H$ and $(\cdot)^\#$, respectively. $\mathbf{I}_m$ represents an $m \times m$ identity matrix, and $\mathbf{0}_{m,n}$ is an $m \times n$ zero matrix.

2. Signal model

Suppose that K independent narrowband sources (FF and NF) impinge upon a symmetric uniform linear array (ULA), as is shown in Fig. 1. This ULA is composed of $N = 2M + 1$ omnidirectional sensors, with the inter-element spacing being d. We assume that there are K_1 sources in the FF and the rest K_2 sources are in the NF, where $K_2 = K - K_1$.

We first formulate the received signal for an ideal array without mutual coupling effects between the array sensors. Therefore, with the array center being the phase reference point, the signal received by the mth sensor can be modeled as

$$x_m(t) = \sum_{k=1}^{K} s_k(t) e^{j\tau_{mk}} + n_m(t) \tag{1}$$

where $s_k(t)$ represents the k-th signal, $n_m(t)$ is the additive noise. The phase shift associated with the k-th signal's propagation time delay from the phase reference point to the mth sensor is denoted as τ_{mk}, which is of the form

$$\tau_{mk} = \frac{2\pi}{\lambda}\left(\sqrt{r_k^2 + (md)^2 - 2r_k md \sin\theta_k} - r_k\right) \tag{2}$$

where θ_k represents the DOA of the k-th source, r_k stands for the distance between the k-th source and the reference sensor, and λ is the wavelength of the source wavefronts.

When the k-th source is in the FF, the distance r_k between the array and the source is much greater than the array aperture size, and therefore τ_{mk} is adequately approximated by [1]

$$\tau_{mk} \approx -\frac{2\pi md}{\lambda} \sin\theta_k. \tag{3}$$

However, in many applications, the source may lie in the NF region of the array, and r_k is on the order of only a few array apertures. Therefore, the expression in (3) is no longer valid. For the NF source, τ_{mk} can be approximated by using the second-order Taylor expansion of (2) [8]

$$\tau_{mk} \approx -\frac{2\pi}{\lambda} md \sin\theta_k + \frac{\pi (md)^2}{\lambda r_k} \cos^2\theta_k = m\omega_k + m^2\phi_k \tag{4}$$

where ω_k are ϕ_k called electric angles and respectively defined as

$$\omega_k = -\frac{2\pi d}{\lambda} \sin\theta_k \tag{5}$$

$$\phi_k = \frac{\pi d^2}{\lambda r_k} \cos^2\theta_k. \tag{6}$$

Note that, in (6), as r_k approaches to $+\infty$, $\phi_k = 0$. As a result, the FF source can be deemed as a limiting case of the NF one.

As discussed in [6], the mutual coupling coefficient (MCC) between two elements is inversely proportional to their distance (i.e., the coefficients between neighboring sensors are almost equal, and it can be approximated as zero when the two sensors are far apart). However, most mixed source localization algorithms constrain the inter-sensor spacing to be within a quarter wavelength. Therefore, the performance of these algorithms would degrade without compensating for mutual coupling.

Assume $\mathbf{C}$ denotes the $N \times N$ MCM of the ULA. It can be modeled as the following banded symmetric Toeplitz matrix with $P + 1$ nonzero MCCs [6], which are arranged in a $P + 1$ vector $\mathbf{c} = [1, c_1, \ldots, c_P]^T = [1, \mathbf{c}_1^T]^T$.

$$\mathbf{C} = toeplitz\{\mathbf{c}\} = \begin{bmatrix} 1 & c_1 & \cdots & c_P & 0 & \cdots & 0 \\ c_1 & 1 & c_1 & \vdots & \ddots & \ddots & \vdots \\ \vdots & c_1 & 1 & \ddots & \vdots & \ddots & 0 \\ c_P & \vdots & \ddots & \ddots & \ddots & \vdots & c_P \\ 0 & \ddots & \vdots & \ddots & 1 & c_1 & \vdots \\ \vdots & \ddots & \ddots & \vdots & \vdots & 1 & c_1 \\ 0 & \cdots & 0 & c_P & \cdots & c_1 & 1 \end{bmatrix} \tag{7}$$

herein, $toeplitz\{\mathbf{c}\}$ symbolizes the construction of a symmetric Toeplitz matrix from the vector $\mathbf{c}$.

Therefore, in a matrix form, the array output vector $\mathbf{x}(t)$ under mutual coupling can be modeled as:

$$\begin{aligned} \mathbf{x}(t) &= \left[x_{-M}(t), \ldots, x_0(t), \ldots, x_M(t)\right]^T \\ &= \sum_{i=1}^{K_1} \mathbf{C}\mathbf{a}(\theta_i, \infty) s_i(t) + \sum_{j=K_1+1}^{K} \mathbf{C}\mathbf{a}(\theta_j, r_j) s_j(t) + \mathbf{n}(t) \end{aligned}$$