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Localization of spatially distributed near-field sources with unknown angular spread shape

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ABSTRACT

In this paper, we propose to localize and characterize coherently distributed (CD) sources in near-field. Indeed, it appears that in some applications, the more the sources are close to the array of sensors, the more they seem to be scattered. It thus appears to be of the biggest importance to take into account the angular distribution of the sources in the joint direction of arrival (DOA) and range estimation methods. The methods of the literature which consider the problem of distributed sources do not handle the case of near field sources and require that the shape of the dispersion is known. The main contribution of the proposed method is to estimate the shape of the angular distribution using an additional shape parameter to address the case of unknown distributions. We propose to jointly estimate the DOA, the range, the spread angle and the shape of the spread distribution. Accurate estimation is then achieved even when the shape of the angular spread distribution is unknown or imperfectly known. Moreover, the proposed estimator improves angular resolution of the sources.

1. Introduction

In array signal processing, most of the algorithms that estimate the direction of arrival (DOA) have been developed on the assumption of point emitting sources in far-field. This modeling assumption is not suitable for several physical examples. Indeed in many applications such as wireless communications, radar, sonar or localization of acoustic sources, the angular spread of the spatial extension cannot be ignored. One can cite as a motivating subject for future study, the localization of aero-acoustic sources on the body of a car [1]. The purpose of such an application is to allow car manufacturers to improve passenger comfort by reducing aerodynamic noise.

Two models are classically used in the literature for spatial distributed sources. In telecommunications, the model considers independent local scatterers around the source [2]. A second widely considered model [3] assumes that the source is continuously spatially extended around a nominal DOA with an angular spread distribution. The present paper is based on the second model. In order to estimate both the DOA and the angular spread of the distributed sources in the far-field case, Valaee proposed the Distributed Signal Parameter Estimator (DSPE) [3] which is a MUSIC-like algorithm [4]. However, the assumption of knowing the distribution function of the spatial extension is not realistic in practice. Besides, such a method suffers from robustness issues with respect to the imperfect knowledge of the angular spread distribution. In other words, an *a priori* information about the angular spread shape must be provided for good performance. A solution based on decoupling the DOA θ from the angular spread Δ

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estimation has been proposed in [5] using the covariance matching method. This method is developed in the case of Incoherently Distributed[1](ID) sources but suffers from ambiguity problem. Zoubir and Wang proposed in [6], a decoupled estimation of the DOA and the angular spread distribution for far-field sources. This method provides a robust estimation only for DOA but it requires the knowledge of the angular spread shape distribution to estimate the angular spread parameter.

Near-field source's localization has been an active field of research for many years [7–11]. As far as we know, the estimators proposed in the literature do not take into consideration the aspect of spatial distributed sources in conjunction with the aspect of near-field propagation. However, for a given physical extension of the source, the angular spread becomes more relevant as the source gets closer to the array.

These reasons motivate us to propose an estimator of CD sources in near-field which is robust to the imperfect knowledge of the angular spread distribution. First, we introduce the model [3] in the near-field context with the aim of considering the angular spread when sources are close to the array. Then, we discuss limits of DSPE algorithm with different angular distribution shapes for the near-field. Finally, we propose a modification of the DSPE which consists in using a generic function family to describe the angular spread distribution. The method called Joint Angle, Distance, Spread, Shape Estimator (JADSSE) consists in the estimation of the distribution shape parameter in addition to the three other parameters.

The contribution is organized as follows. In Section 2, we extend the model for distributed sources located in near-field. In Section 3, we present the generalization of the DSPE and the new JADSSE method. In Section 4, the performance of the proposed algorithms is compared by numerical simulations. Finally we present the conclusions.

2. Signal model

Let us assume q spatially distributed narrow-band near-field sources impinging on a Uniform Linear Array (ULA) of M sensors. The distance between two adjacent sensors is $d=\lambda/2$, where λ is the wavelength of the signals. We also suppose that the sources and the sensors are in the same plane. The $M\times 1$ baseband signal vector measured by the M sensors is given by $\underline{\mathbf{x}}(t)=[x_1(t),\ldots,x_M(t)]^T$, where $(.)^T$ is the transpose operator. Authors in [3] proposed a model for the distributed sources in far-field. We here extend this model in the near-field context, considering an angular spread of DOA[2]:

$$\underline{\mathbf{x}}(t)=\sum_{i=1}^{q}\int_{-\pi/2}^{\pi/2}\underline{\mathbf{a}}(\phi,r_i)v_i(\phi,\theta_i,\Delta_i,t)\,d\phi+\underline{\mathbf{n}}(t). \quad (1)$$

$v_i(\phi,\theta_i,\Delta_i,t)$ denotes the signal angular distribution for the i-th source. θ_i is the central DOA for the source and Δ_i is the angular spread. $\underline{\mathbf{n}}(t)$ is the $M\times 1$ white additive noise vector. The $M\times 1$ vector $\underline{\mathbf{a}}(\phi,r)$ represents the near-field array response for a source located in direction ϕ and at range r.

In the near-field context, the signal propagation time between sensor m and a reference sensor (e.g the first one) can be approximated[3] (see [12] for details). In this case, the $(m+1)$-th element of the steering vector $\underline{\mathbf{a}}(\phi,r)$ is expressed as

$$a_{m+1}(\phi,r)=\exp\left(-j\pi\,\sin(\phi)m+j\frac{\pi\lambda}{4r}\cos^2(\phi)m^2\right). \quad (2)$$

Throughout the paper, we consider that the sources are coherently distributed (CD). A CD source is described by a temporally invariant angular distribution and the components of the signal are fully correlated for the whole angular spread (for more details see [3]). Thus, the signal angular distribution for the i-th CD source can be expressed by

$$v_i(\phi,\theta_i,\Delta_i,t)=s_i(t)h_i(\phi,\theta_i,\Delta_i), \quad (3)$$

where $s_i(t)$ is a random complex signal emitted by the i-th source and $h_i(\phi,\theta_i,\Delta_i)$ represents a deterministic angular spread distribution. For multiple CD sources, the model of the received signal for q sources in near-field is given by

$$\underline{\mathbf{x}}(t)=\sum_{i=1}^{q}s_i(t)\underline{\mathbf{c}}(\theta_i,\Delta_i,r_i)+\underline{\mathbf{n}}(t), \quad (4a)$$

$$\underline{\mathbf{c}}(\theta_i,\Delta_i,r_i)=\int_{-\pi/2}^{\pi/2}\underline{\mathbf{a}}(\phi,r_i)h_i(\phi,\theta_i,\Delta_i)\,d\phi, \quad (4b)$$

where $\underline{\mathbf{c}}(\theta_i,\Delta_i,r_i)$ is the vector obtained by integrating the steering vector $\underline{\mathbf{a}}(\phi,r_i)$ with the angular distribution of the i-th source $h_i(\phi,\theta_i,\Delta_i)$. The source signal and noise time samples are modeled by random, complex, centered and independent processes. We assume that the noise and the sources $v_i(\phi,\theta_i,\Delta_i,t)$ are uncorrelated with each other. Considering the previous assumptions, the correlation matrix of the array output is given by

$$\mathbf{R}_{xx}=E[\underline{\mathbf{x}}\underline{\mathbf{x}}^H]=\mathbf{CSC}^H+\sigma^2\mathbf{I}, \quad (5)$$

where $E[.]$ is the statistical expectation operator, $\mathbf{C}$ is the $M\times q$ matrix containing the column vectors $\underline{\mathbf{c}}(\theta_i,\Delta_i,r_i)$ for $i=1,\ldots,q$, $\mathbf{S}$ is the sources correlation matrix with the ij-th component defined as $s_{ij}=E[s_is_j^*]$, σ^2 is the noise variance and $\mathbf{I}$ is the $M\times M$ identity matrix. The sources are assumed to be uncorrelated with each other, so that $\mathbf{S}$ is diagonal. The correlation matrix $\mathbf{R}_{xx}$ can be estimated from the L snapshots by

$$\hat{\mathbf{R}}_{xx}=\frac{1}{L}\sum_{l=1}^{L}\underline{\mathbf{x}}(t_l)\underline{\mathbf{x}}^H(t_l). \quad (6)$$

3. Proposed estimators

In this section, we present two methods of joint angle, spread and range estimation for the localization of CD sources in near-field. First, we introduce an extension of

[1] Signals arriving from multiple directions are assumed to be uncorrelated.

[2] Similarly a range spread can also be considered, however, in order to make the paper more readable we only consider the angular spread.

[3] Approximation of the propagation time is not necessary to extend the model [3] in the near-field and the propagation time can be also used in its general form.