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On the introduction of an extended coupling matrix for a 2D bearing estimation with an experimental RF system[☆]

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Abstract

Narrow-band DOA (direction of arrival) estimation methods need an accurate modeling of the array manifold (response of the array of antennas to one source in all directions). In radio frequency (RF) systems, electromagnetic perturbations arising from the neighborhood of the array will bring differences between the ideal and the true or measured response. If the model of the array response used in the algorithms does not take this modeling error into account, the performance of the bearing estimation methods may degrade dramatically. Usually, either a data collection of true steering vectors or a mutual-coupling model are used to perform DOA estimation in an experimental setup. The purpose of this paper is to propose an alternative to the mutual-coupling model by deriving a more accurate analytic expression of the true response. We present a model using a new extending coupling matrix, which includes the polarization and the scattering elements of the array in addition to mutual-coupling effects. An estimation of these extended and mutual coupling matrices is also originally proposed when measurements of the true steering vectors are available. The true steering vectors are measured in an experimental setup. Based on these new analytical expressions of the steering vectors of the array response, we extend the MUSIC DOA estimation algorithm to polarization diversity.

Keywords: DOA estimation; Calibration; Polarization; Coupling matrix; High-resolution methods; MUSIC

1. Introduction

Over the last three decades, a large number of high-resolution direction finding techniques have been developed in order to estimate the DOAs (directions of arrival) of sources impinging on an array of antennas [1–6]. These techniques can be used in a radio-communication context to estimate the DOAs of correlated or coherent sources such as the propagation paths of the different emitters. In such a context, accurate DOA estimation methods as high-resolution methods are required to provide efficient estimates.

These high-resolution direction finding algorithms need an accurate knowledge of the spatial array response (array manifold) of the sources. If this array manifold is not accurately known, the performance of the high-resolution methods will degrade dramatically [7]. In experiments, one of the

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Nomenclature

a	scalar
$\mathbf{a}$	column vector
a_i	ith component of the column vector $\mathbf{a}$
$(.)^{\mathrm{T}}$	transpose
$(.)^{\dagger}$	Hermitian transpose
$\det(\mathbf{A})$	determinant of matrix $\mathbf{A}$
$\mathbf{I}_N$	$N \times N$ identity matrix
θ	azimuth
Δ	elevation
$(.)^{(\mathrm{H}),(\mathrm{V})}$	scalar, vector or matrix associated to the horizontal or vertical polarization
$\mathbf{\Phi}$	polarization vector of horizontal and vertical components $\Phi^{(\mathrm{H})}$ and $\Phi^{(\mathrm{V})}$: $\mathbf{\Phi} = [\Phi^{(\mathrm{H})}\ \Phi^{(\mathrm{V})}]^{\mathrm{T}}$
$\mathbf{\Theta} = (\theta, \Delta)$	direction of arrival
$\mathbf{a}(\mathbf{\Theta})$	geometrical steering vector without diverse polarization
$\mathbf{a}(\mathbf{\Theta}, \mathbf{\Phi})$	$= \mathbf{a}^{(\mathrm{H})}(\mathbf{\Theta})\Phi^{(\mathrm{H})} + \mathbf{a}^{(\mathrm{V})}(\mathbf{\Theta})\Phi^{(\mathrm{V})}$: geometrical steering vector with diverse polarization
$\mathbf{a}_e(\mathbf{\Theta}, \mathbf{\Phi})$	$= \mathbf{a}_e^{(\mathrm{H})}(\mathbf{\Theta})\Phi^{(\mathrm{H})} + \mathbf{a}_e^{(\mathrm{V})}(\mathbf{\Theta})\Phi^{(\mathrm{V})}$: exact steering vector
$\widetilde{\mathbf{a}}^{(\mathrm{H}),(\mathrm{V})}(\mathbf{\Theta})$	steering vector model associated to the horizontal (H) or vertical (V) polarization component
$\widetilde{\mathbf{a}}(\mathbf{\Theta}, \mathbf{\Phi})$	$= \widetilde{\mathbf{a}}^{(\mathrm{H})}(\mathbf{\Theta})\Phi^{(\mathrm{H})} + \widetilde{\mathbf{a}}^{(\mathrm{V})}(\mathbf{\Theta})\Phi^{(\mathrm{V})}$: steering vector modeling
$\mathbf{Z}_0$	mutual coupling matrix
$\mathbf{Z}_b$	body coupling matrix
$\mathbf{Z}^{(\mathrm{H}),(\mathrm{V})}$	extended coupling matrix associated to the horizontal (H) or vertical (V) polarization component

main reason of such model miss-match is due to the electromagnetic perturbations on the antennas of the array. A typical example of perturbations are the electromagnetic reflections between elements of the array (sensors and/or structures) that lead to a distortion of the nominal ideal expression of the array manifold.

A first alternative to overcome these perturbations is to use a data collection of exact steering vectors that is the numerical recording in an experimental setup of the array response for different directions covering the electromagnetic field of view. It is the calibration process [8]. The main drawbacks of such a technique lie firstly in the cost of this data collection procedure and secondly in the fact that it leads to a non-continuous knowledge of the array manifold. Also, the resolution is limited by the angular sampling of the electromagnetic field of view.

A second alternative which is the purpose of this paper is to elaborate a "compensated" expression of the steering vectors of the array manifold. A first approach taking into account mutual-coupling (inter-sensors) array perturbations has been proposed in [9–13]. In the papers [10–12], adaptations of the MUSIC algorithm and spatial-smoothing techniques using the mutual-coupling model (MCM) are proposed for a uniform linear array. These methods only take into account the mutual-coupling between sensors of the array and perform only a single dimensional (1D) DOA estimation. In [9] mutual coupling electronic measurements have been proposed. This method consists in the effective electronic measure of the transfer function between two elementary antennas of the array. However, this approach requires the capability of each antenna to receive or transmit independently from the other antennas. In practice, this is not always possible. Moreover, this method does not allow an estimation of the coupling coefficients between the elements of the structure (mast and arms) and the elementary sensors. As an alternative, the MoM (method of moments) might be used to derive a closed form expression of the mutual coupling matrix [14–16]. However, this last numerical approach requires the knowledge of the precise antennas shape.

In addition, a bearing estimation setup generally uses an array composed of the antennas and the metallic structures that behave as external scatters. Unfortunately, electronic measurements proposed in [9] and the MoM cannot estimate the coupling parameters between the antennas of the arrays and the external scattering elements.

The aim of this paper is to identify and propose a model for the additional perturbations brought by the structure of the array. The resorting coupling will be called "extended-coupling" throughout this paper. The introduction of such an extended-coupling matrix will provide a more accurate analytical model of the array manifold (or array response) leading to a more efficient use of bearing estimation methods.

The paper is organized as follows: in Section 2 the formulation of the problem is stated. In Section 3