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Experimental antenna array calibration with artificial neural networks

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Abstract

It is well known that to perform accurate Direction of Arrivals (DOA) estimation using algorithms like MUSIC (MUltiple SIgnals Classification), antenna array data must be calibrated to match the theoretical model upon which DOA algorithms are based. This paper presents experimental measurements from independent sources obtained with a linear antenna array and proposes a novel calibration technique based on artificial neural networks trained with experimental and theoretical steering vectors. In this context, the performance of 3 types of neural networks—ADAptive LInear Neuron (ADALINE) network, Multilayer Perceptrons (MLP) network and Radial Basis Functions (RBF) network—is assessed. This is then compared with other calibration techniques, thus demonstrating that the proposed technique works well while being very simple to implement. The presented results cover operation with a single signal source and with two uncorrelated sources. The proposed method is applicable to arbitrary array topologies, but is presented herein in conjunction with a uniform linear array (ULA).

Keywords: Antenna arrays; Calibration; Artificial neural networks; Array processing; Beamforming; DOA; MUSIC

1. Introduction

Array antenna usage in various communication, radar and instrumentation systems has been growing dramatically over the last few years for several reasons. The emergence of new antenna shapes simplified their production, given their simplicity. Several such antennas can be integrated, together with some circuitry, into a monolithic small-scale device, effectively resulting in low-cost, diminutive antenna arrays. The advent of increasingly cheaper signal processing chips (DSP) makes possible the sophisticated processing of the plurality of signals from an antenna array at a low-cost, low-power consumption, and in a small form factor. Given the digital processing power available to analog to digital interface can be moved closer to the antenna, thus reducing the complexity and cost of the RF section. This core signal processing itself can take various forms, can include parameter estimation, adaptive filtering and detection.

In the case of this present work, two well-known classes of space-time processing algorithms are of interest: beamforming and Direction of Arrivals (DOA) estimation.

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However, in a real-world, there are some reasons which limit the general use of antenna arrays. One of them is the precise calibration required such arrays when they are used for specific tasks, such as beamforming and DOA estimation which require the acquisition of the precise amplitude and phase relationships of the signals collected at each element. These relations are unfortunately sensitive to many potential error sources, leading to severe performance constraints. First, phase and gain imbalances between the in-phase (I) and quadrature (Q) branches of each element receiver/transmitter subsystem and the I/Q bias errors due to electronic DC offsets cause a divergence from the statistical model upon which signal processing algorithms depend; more details on this source of error are available in [1,2]. Indeed, the said algorithms are constructed based on various assumptions, such as the ideal properties of complex Gaussian variates originally postulated by Goodman [3]. Another deviation between theory and practice is due to the co-channel gain and phase errors, i.e. the variations between the multiple element receiver/transmitter subsystems themselves. The third error source is the mutual coupling effects between the elements comprising the array. The fourth error source in an experimental antenna array setup is the element location errors or uncertainties. Finally, scattering by the antenna mounting structure or other nearby structures constitutes a fifth source. These causes of errors can be considered statics during a sufficient period of time.

All of these perturbations consequently affect the specific structure of the data covariance matrix. Furthermore, the theoretical steering vectors can find themselves outside the experimental signal subspace. These effects imply a poor or erroneous performance by signal processing algorithms, as can be seen in Section 5 and in [4,5] which analyze the performance of these algorithms in the presence of model errors.

The solution to all of these problems is inevitably some form of data calibration to fit the theoretical model or, equivalently, the experimental array manifold calibration with respect to the presumed steering vectors set. Fig. 1 shows a schematic representation of a linear uniformly spaced antenna array used to perform DOA estimation for M sources. The RF front-end is detailed in Section 5 while the digital processing apparatus is discussed in Sections 2 and 4.

A lot of contributions can be found in the literature on the topic of antenna array calibration. Most are based only on simulation, which by itself probably yields an incomplete picture of this essentially experimental issue. These works can collectively be slated into three main approaches. First, some authors [6] attempt to bypass the calibration problem by constructing a new data covariance matrix which has a Toeplitz structure. The second class is referred to as *auto calibration* or *online calibration*, because it does not require knowledge of the directions of the calibrating sources. Finally, the last approach is designated *trained calibration* or *offline calibration* and it implies knowledge of the calibrating sources' (pilots) exact bearings.

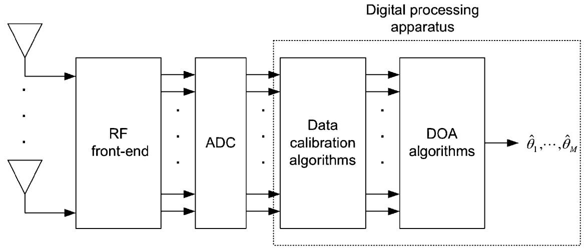

Fig. 1. A schematic representation of a linear equispaced array receiver performing DOA estimation.

The first approach is only applicable in the case where sensor location errors alone are present. The second one is generally iterative and is not really self-sufficient, because such algorithms, globally based on some form of least-squares fit, require initial calibration [7–12], some a priori information about a received signal (such as a CDMA code [7,8]) and/or it is assumed that part of the response is known (like in [13] where the sensor gains are assumed known). Also, these iterative algorithms can potentially converge to a local minimum rather than the global one if the initial conditions are not sufficiently close to the solution [7,10,14–16]. Furthermore, the majority of these pseudo-self-calibration algorithms have been studied by focusing on one or more error sources, but rarely on all. For example, [12,17–20] focus only on the amplitude and/or phase errors, [21] on mutual coupling and scattering, [22–25] on I/Q imbalances and [15,26] on sensor position errors or uncertainties. Also, some techniques [27,28] necessitate a different calibration step for each error source.

On the other hand, training-based calibration requires knowledge of the calibrating sources' angular positions [4,12,14,29–32]. As explained