Antenna Arrays Diagnosis Through Inverse-Based Approaches

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Abstract

Two effective regularization approaches for detecting faults in antenna arrays are discussed in this paper. The first one exploit the matrix method for fast and low-cost diagnostics. The second technique relies upon an inversion scheme in Lebesgue spaces, allowing an effective regularization of the problem. Preliminary results are discussed, showing the effectiveness of the approaches.

1. Introduction

Fault detection is an important task in modern antenna array measurement and testing. Indeed, large arrays are typically required in modern applications, such as communication and radar imaging, where the presence of defective elements may affect the radiation properties and the overall antenna performances.

In order to address this task, several approaches have been proposed in the scientific literature in the past years [1]–[4]. Usually, the fault detection problem is faced by resorting to an inverse problem, in which the excitation coefficients (or current distribution over the array) are retrieved starting from the field radiated by the antenna under test. However, this inverse problem poses several issues. Indeed, it turns out to be severely ill-posed; consequently, proper regularization procedure needs to be adopted in order to obtain meaningful results. Moreover, especially when dealing with high-frequency arrays (e.g., working in the mm-band), phase measurements may be not fully reliable.

In this paper, two approaches for solving in a regularized sense the fault detection problem are discussed. The first technique, referred as matrix method [5], relies upon the adoption of a truncated Singular Value Decomposition (SVD) scheme combined with a dimensionality reduction strategy, allowing fast and low-effort diagnostics of large arrays. The second approach adopts a Landweber-like inversion technique in Lebesgue spaces L^p [6] to solve in a regularized sense the inverse problem at hand, which can be tuned with a proper choice of the norm parameter (e.g., for enhancing sparsity in the solution). Preliminary results showing the effectiveness of the approaches are discussed.

The paper is organized as follows. Section II presents an overview of the formulation for the considered array diagnostic approaches. Section III reports some preliminary results. Finally, Section IV draws some conclusions.

2. Mathematical Formulation: Overview

An overview of the considered fault detection algorithms is reported in this Section. In particular, a planar array consisting of $N = N_x \times N_y$ radiating elements which are positioned in the x-y plane at positions $\mathbf{r}_{ant}^n$ is assumed (see Figure 1). The excitation coefficients of the elements are denoted as a_n, $n = 1, \dots, N$. The diagnosis of the array is performed starting from samples of the field radiated by the array and measured in a set of M probing points which are located on a measurement surface $\mathcal{M}$ at positions $\mathbf{r}_{meas}^m$, $m = 1, \dots, M$.

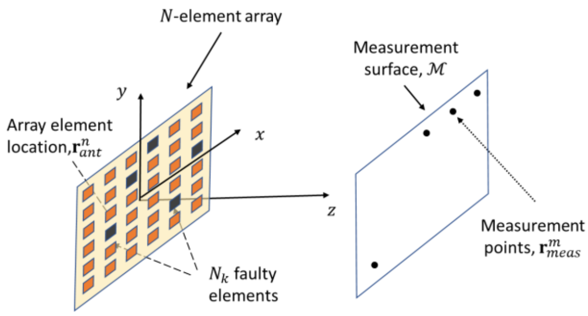

Figure 1. Antenna array diagnostics: configuration.

As it is well known, it is possible to relate the field samples to the excitations coefficients through a linear mapping [7], i.e.,

$$\underline{b} = [H]\underline{a} \tag{1}$$

where the arrays $\underline{a}$ and $\underline{b}$ contain the N excitation coefficients and the M measurements of the radiated field, whereas the matrix $[H]$ is the discrete representation of the considered radiation operator. Specifically, the matrix $[H]$ can be expressed in terms of the near-, $\psi_{NF,n}$, or far-field, $\psi_{FF,n}$, element patterns [8], [9], i.e.,

$$[H]_{mn} = \begin{cases} \psi_{NF,n}(\mathbf{r}_{meas}^m) & \text{Near-field} \\ \psi_{FF,n}(\theta_m, \phi_m) e^{jk_0 \hat{\mathbf{r}}_m \cdot \mathbf{r}_{ant}^n} & \text{Far-field} \end{cases} \tag{2}$$

where k_0 is the vacuum wavenumber and (θ_m, ϕ_m) is the direction of the m-th sampling point and $\hat{\mathbf{r}}_m = \sin\theta_m \cos\phi_m \,\hat{\mathbf{x}} + \sin\theta_m \sin\phi_m \,\hat{\mathbf{x}} + \cos\theta_m \,\hat{\mathbf{z}}$.

Specifically, the fault detection problem involves the determination of the excitation coefficients $\underline{a}$. This can be

achieved by inverting (2). However, such equation is usually significantly ill-conditioned, thus specific regularization strategies are required. To this end, two approaches are considered in this work.
In the first one, referred as *Matrix Method*, matrix $[H]$ is uniformly sampled, and a fast SVD approach is applied to detect faulty elements [5].
In the second one, a Landweber-like technique developed in the framework of Lebesgue spaces L^p is adopted to invert (2) in a regularized sense [6]. Specifically, the approach iteratively minimize the residual function $R(\underline{a}) = 0.5\left\|[H]\underline{a} - \underline{b}\right\|_p^2$ by moving along non-standard gradient descent directions in the dual spaces. This is achieved through the following iterates (initialized with a null solution, i.e., $\underline{a}_0 = 0$, and stopped when a proper termination criteria is satisfied)

$$\underline{a}_{i+1} = J_{p^*}\left(J_p(\underline{a}_i) - \beta[H]^* J_p([H]\underline{a} - \underline{b})\right) \quad (3)$$

where J_{p/p^*} denotes the duality maps [6], $p^* = p/(p-1)$ being the Holder conjugate of p, and $\beta > 0$ is the step length. Details on the inversion procedure an be found in [6].

3. Preliminary Numerical Results

Some preliminary numerical results are reported in this Section.
Concerning the Matrix Method approach, numerical validations are performed by considering an array of 5 x 5 elementary sources, with a $\lambda_0/2$ inter-element spacing (λ_0 being the wavelength in vacuum). The second row of the array is assumed to contain faulty elements, and near-field data are numerically simulated on a plane $5\lambda_0$ away from the array. Matrix [H], representing the radiation operator, is then computed from eq. (2), and the fast SVD approach is applied, after performing the uniform sampling of [H], to detect faulty elements [5]. These are accurately identified from the excitation coefficients, as reported in Fig. 2.

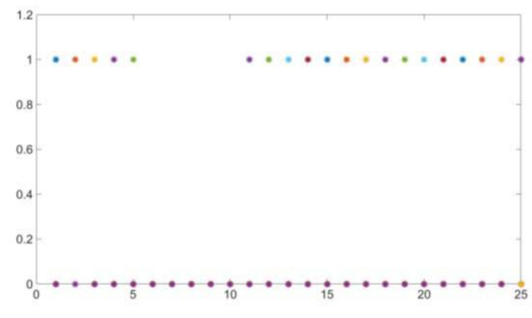

Figure 2. Reconstructed distribution of the excitation coefficients. Matrix Method approach.

Concerning the Lebesgue-space approach, an array of 5×5 patch antennas working at 2.4 GHz has been initially considered. The inter-element spacing has been set to $\lambda_0/2$ (λ_0 being the wavelength in vacuum). Uniform excitation coefficients are used. A subset of $N_k = 3$ faulty elements has been randomly introduced (full faults are assumed). A differential approach has been followed, in which it is assumed to have at disposal a set of measurements $\underline{b}_{ref}$ of the fully working array, along with the corresponding excitation coefficients $\underline{a}_{ref}$. In this way, the fault detection problem can be rewritten in terms of the failure vector $\Delta\underline{a} = \underline{a} - \underline{a}_{ref}$. $M = 325$ sampling point equally spaced on a hemisphere in the far-field region are considered (numerically simulated through a FDTD code). The parameters of the inversion method has been set equal to: norm exponent $p = 1.2$; maximum iteration equal to 100; iterations are stopped when the relative variation of the residual falls below 10^{-3}. Figure 3 shows the reconstructed failure vector. As can be seen, the developed approach allows to effectively detect all the defective elements.

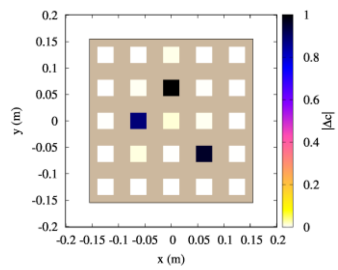

Figure 3. Reconstructed distribution of the failure vector. Lebesgue-space inversion approach.

6. Conclusions

Fault detection in antenna arrays has been tackled in this paper. In particular, two approaches have been considered. The first one is a matrix method that allows fast and low-effort diagnostics of large arrays. The second technique is based on an inversion procedure in Lebesgue space that performs an effective regularization of the problem at hand. Preliminary results show that the fault detection can be achieved in a very effective way. The proposed approach can be successfully applied to solve the antenna diagnostics problem in the presence of high number of elements.

7. Acknowledgements

This work was partly supported by the European Union - Next Generation EU under the Italian National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.3, CUP D43C22003080001, partnership on “Telecommunications of the Future” (PE00000001 - program “RESTART”).

References

[1] A. Dell’Aversano, A. Natale, A. Cuccaro, and R. Solimene, “Linear array antenna diagnostics through a MUSIC algorithm,” *IEEE Access*, **7**, 2019, pp.

176952–176959, doi: 10.1109/ACCESS.2019.2956680

[2] A. Patnaik, B. Choudhury, P. Pradhan, R. K. Mishra, and C. Christodoulou, "An ANN application for fault finding in antenna arrays," *IEEE Transactions on Antennas and Propagation*, **55**, 3, March 2007, pp. 775–777, doi: 10.1109/TAP.2007.891557

[3] B. Fuchs, L. L. Coq, and M. D. Migliore, "Fast Antenna Array Diagnosis from a Small Number of Far-Field Measurements," *IEEE Transactions on Antennas and Propagation*, **64**, 6, June 2016, pp. 2227–2235, doi: 10.1109/TAP.2016.2547023

[4] R. Palmeri, T. Isernia, and A. F. Morabito, "Diagnosis of Planar Arrays Through Phaseless Measurements and Sparsity Promotion," *IEEE Antennas and Wireless Propagation Letters*, **18**, 6, June 2019, pp. 1273–1277, doi: 10.1109/LAWP.2019.2914529

[5] G. Di Massa and S. Costanzo, "Fast diagnostics of conformal arrays," *Advances in Intelligent Systems and Computing*, 2018, pp. 1494–1501, doi: 10.1007/978-3-319-77712-2_145

[6] V. Schenone, A. Fedeli, C. Estatico, M. Pastorino, and A. Randazzo, "Detection of failures in antenna arrays through a Lebesgue-space approach," *IEEE Open Journal of Antennas and Propagation*, **3**, 2022, pp. 652–662, doi: 10.1109/OJAP.2022.3181345

[7] C. A. Balanis, *Antenna theory: Analysis and design*, 4th ed. Hoboken, NJ: John Wiley & Sons, 2016

[8] R. Palmeri, G. M. Battaglia, A. F. Morabito, S. Costanzo, F. Venneri, and T. Isernia, "Fault diagnosis of realistic arrays from a reduced number of phaseless near-field measurements," *IEEE Transactions on Antennas and Propagation*, **71**, 9, September 2023, pp. 7206–7219, doi: 10.1109/TAP.2023.3293004

[9] M. Salucci, A. Gelmini, G. Oliveri, and A. Massa, "Planar array diagnosis by means of an advanced Bayesian compressive processing," *IEEE Transactions on Antennas and Propagation*, **66**, 11, November 2018, pp. 5892–5906, doi: 10.1109/TAP.2018.2866534