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An Experimental Study of Antenna Array Calibration

Inder J. Gupta, James R. Baxter, Steven W. Ellingson, Hyung-Geun Park, Hyun Seo Oh, and Mun Geon Kyeong

Abstract—The coupling matrix concept for predicting the radiation patterns of elements of an antenna array is studied. Measured data, as well as some numerical data, are used in the study. It is demonstrated that for some practical antennas of interest whose radiation patterns are affected by structure scattering, the coupling matrix concept may not work very well. As expected, the stronger the structure scattering, the greater the discrepancy between the predicted patterns and the actual patterns.

Index Terms—Antenna calibration, coupling matrix, structure scattering.

I. INTRODUCTION

For angle-of-arrival (AoA) estimation and certain smart antenna processing techniques, one needs to know the array manifold for all incidence angles. This requirement can be relaxed if the array manifold depends entirely on the antenna geometry and radiation pattern of a single antenna in free space. In practice, this is rarely true. The coupling between various elements of an antenna array as well as scattering by the antenna mounting structure and/or other nearby structure affects the array manifold. Also, there will be differences among the cabling and receivers used to down convert and digitize the signals from each antenna element. All of these effects have the potential to vary in both time and frequency, making the array manifold very difficult to anticipate/estimate. The process of obtaining the array manifold is called antenna-array calibration.

Many different algorithms [1]–[5] have been reported in the literature for antenna-array calibration. Most of these algorithms depend on the assumption that the voltages received by an N element antenna array for a signal incident from direction ϕ can be written as

$$\mathbf{b}(\phi) = \mathbf{C}\mathbf{Z}\mathbf{a}(\phi) \quad (1)$$

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I. j. Gupta, J. R. Baxter, and S. W. Ellingson are with the The Ohio State University ElectroScience Laboratory, Department of Electrical Engineering, Columbus, OH 43212 USA.

H. G. Park, H. S. Oh, and M. G. Kyeong are with Electronics and Telecommunications Research Institute, (ETRI) Daejeon, Korea.

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where \mathbf{b} is an $N \times 1$ vector of the measured voltages, \mathbf{C} is an $N \times N$ matrix which represents variations in the complex gain among antennas, feedlines, and receivers, \mathbf{Z} is an $N \times N$ matrix representing the effect of antenna-to-antenna coupling and structure scattering, and $\mathbf{a}(\phi)$ is an $N \times 1$ vector describing the received voltages in the absence of antenna-to-antenna coupling and structure scattering. Note that $\mathbf{a}(\phi)$ depends only on the antenna geometry and the radiation pattern of a single antenna element. Let us say that we are interested in the antenna effects only. In that case, matrix \mathbf{C} can be replaced with an identity matrix and (1) can be written as

$$\mathbf{b}(\phi) = \mathbf{Z}\mathbf{a}(\phi). \quad (2)$$

Assuming that the antenna geometry is known, then according to (2), one needs to know only \mathbf{Z} to predict the antenna array manifold for any ϕ . The question is how to estimate \mathbf{Z} ? Various algorithms to estimate \mathbf{Z} are given in the references cited. The simplest of these assumes that the vector $\mathbf{b}(\phi)$ is measured for M independent (widely separated and not coincident with grating lobes), directions such that $M \geq N$. Let these measurements be represented by the $N \times M$ matrix $\mathbf{B}_M = [\mathbf{b}_1 \mathbf{b}_2 \cdots \mathbf{b}_M]$. Then (2) can be rewritten as [3]

$$\mathbf{B}_M = \mathbf{Z}\mathbf{A}_M \quad (3)$$

where $\mathbf{A}_M = [\mathbf{a}_1 \mathbf{a}_2 \cdots \mathbf{a}_M]$. (3) is an overdetermined set of linear simultaneous equations. The least square solution for \mathbf{Z} is given by

$$\mathbf{Z} = \mathbf{B}_M \mathbf{A}_M^H \left(\mathbf{A}_M \mathbf{A}_M^H \right)^{-1}. \quad (4)$$

Next, one can use this \mathbf{Z} to predict $\mathbf{b}(\phi)$ for any ϕ . However, (2), in general, does not have a way to deal with structure scattering because it (structure scattering) cannot be described in a few parameters. For large antenna arrays, where structure scattering affects all the antenna elements in a similar fashion, one may be able to find an appropriate \mathbf{Z} , provided that the embedded element pattern includes structure scattering effects. For small antenna array the same may not be true. To test this hypothesis, we built two experimental antenna arrays. The radiation patterns of these antenna arrays were measured in The Ohio State University compact range [6]. The measured patterns for a few directions were then used to estimate matrix \mathbf{Z} . Next, matrix \mathbf{Z} is used to predict \mathbf{b} for all angles. In this communication, the predicted results are compared with the measured results. It is shown that for the two antenna arrays, (2) does not work very well. The same is demonstrated using numerical results [method of moments (MoM) solution] for a simple antenna array.

The rest of the communication is organized as follows: The experimental antenna arrays and their measured and estimated patterns are discussed in Section II. Section III contains the numerical results from the simulated array. Finally, Section IV contains a summary and the general conclusions of this work.

II. EXPERIMENTAL ANTENNA ARRAYS

The experimental antenna arrays are linear arrays of eight elements each and are designed to operate around 2.45 GHz. One of the antenna arrays has small interelement spacing ($\sim 0.4\lambda$), whereas, the other antenna element has large interelement spacing ($\sim 0.75\lambda$). The details of these antennas and their measured and predicted patterns are discussed in this section.

A. Antenna Array #1

The first antenna array, shown in Fig. 1, consists of eight printed dipoles. Each printed dipole is fed by a coaxial cable through a $\lambda/4$



Fig. 1. Photograph of an eight-element linear array of printed dipoles.

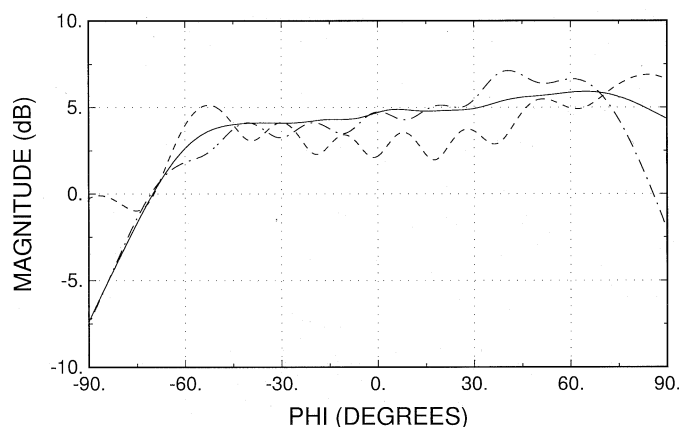


Fig. 2. Radiation pattern of element #1 of the linear array of dipoles at 2.45 GHz. (—) measured pattern, (- - -) predicted pattern with the single element in front of the small plate, and (- · - ·) predicted pattern with the single element in front of the large plate.

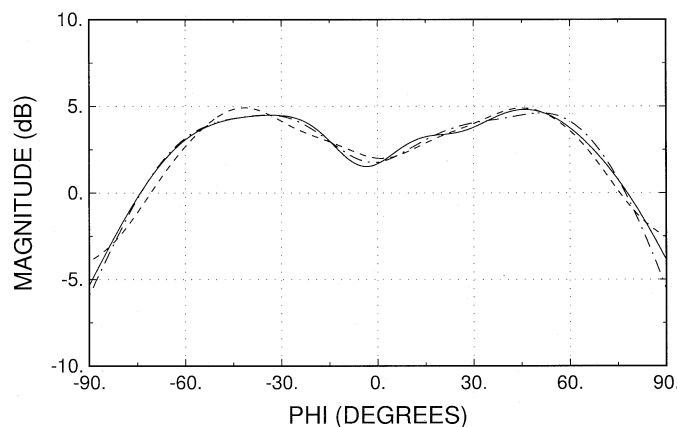


Fig. 3. Radiation pattern of element #4 of the linear array of dipoles at 2.45 GHz. (—) measured pattern, (- - -) predicted pattern with the single element in front of the small plate, and (- · - ·) predicted pattern with the single element in front of the large plate.

stripline balun, and is attached to a 5-cm wide \times 24-cm high aluminum plate for handling and mounting purposes. Thus, the interelement spacing is approximately 5 cm. The antenna array is supported by a vertical conducting rod. The radiation pattern of the single antenna element by itself, and the radiation patterns of various elements of the antenna array were measured in The Ohio State University compact range at 2.45 GHz and vertical polarization in an azimuthal plane (H plane). The radiation pattern of the single dipole was measured when it was attached to the 5-cm-wide plate as well as when it was attached to a 40 cm \times 24-cm plate.

The solid curves in Figs. 2 and 3 show the measured patterns of elements 1 and element 4, respectively, of the antenna array. The elements are numbered from left to right. The broken and dash-dot curves in these figures show the predicted pattern using the coupling matrix approach. For the broken curve, the coupling matrix is estimated using the radiation pattern of the single element in front of the narrow strip; whereas, for the dash-dot curve the radiation pattern of the single element in front of the large plate is used in estimating \mathbf{Z} . Nineteen direc-

tions equally spaced between -90° to 90° angular region are used in estimating \mathbf{Z} . Note, that the predicted patterns, specially for element 1, does not match very well with the measured pattern. The reason for this is that the structure scattering experienced by elements 1 is somewhat different from the reference element (single element in front of a plate). Thus, the structure scattering for this antenna cannot be accounted for by using (2).

B. Antenna Array #2

The second antenna array uses off-the-shelf antenna elements (model P-2406, Astron Antenna Company, Sterling, VA). This antenna element covers a 2.35- to 2.55-GHz frequency band and has a good front-to-back ratio. The width of an antenna element is approximately 9 cm. Fig. 4 shows a photograph of the eight-element antenna array. The elements are mounted on a horizontal angle bracket and the antenna array is fastened to a vertical bar for field measurements. The elements are oriented for vertical polarization; 60 cm below the antenna array, there is another element. This antenna

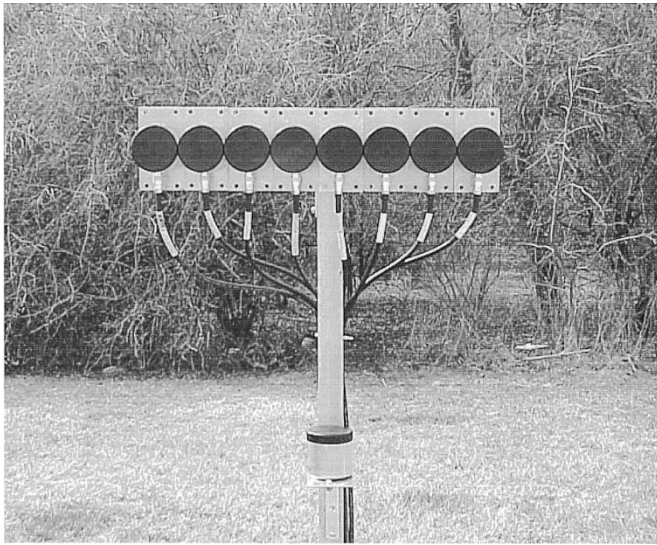


Fig. 4. Photograph of an eight-element linear array of model P-2406 antennas.

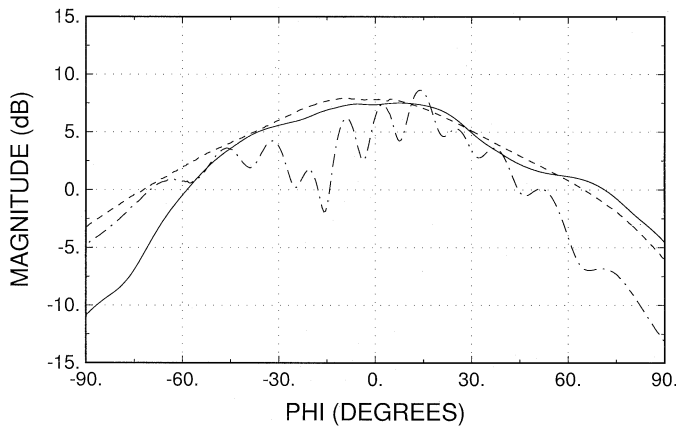


Fig. 5. Radiation pattern of element #1 of the linear array of model P-2406 antennas at 2.45 GHz. (—) measured pattern, (---) predicted pattern with identity coupling matrix, and (- · - ·) predicted pattern with calculated coupling matrix.

element was used to transmit a weak signal for calibration of the feedlines and multichannel receiver in field experiments.

Using a Hewlett-Packard network analyzer, antenna-to-antenna coupling (s_{12} measurements) between various antenna elements was measured. The coupling between adjacent elements, which was found to be very weak, was approximately -25 dB. Thus, the coupling matrix (\mathbf{Z}) for this antenna is essentially an identity matrix. Next, the radiation pattern of a single antenna element and the radiation patterns of various elements of the antenna array were measured at 2.45 GHz along an azimuthal plane (H plane). The solid curves in Figs. 5 and 6 show the measured patterns of elements 1 and 4, respectively, of the antenna array. The broken curves in Figs. 5 and 6 show the predicted patterns using (2) when the coupling matrix is assumed to be an identity matrix. Note that the predicted radiation patterns do not match the measured patterns. The coupling matrix approach, therefore, cannot be used to predict the radiation patterns when the structure scattering is dominant. The dash-dot curves in these figures show the predicted patterns when (4) is used to estimate the coupling matrix. Again, 19-directions equally-space between the -90° to 90° angular region are used to estimate the coupling matrix. The estimated coupling matrix showed large

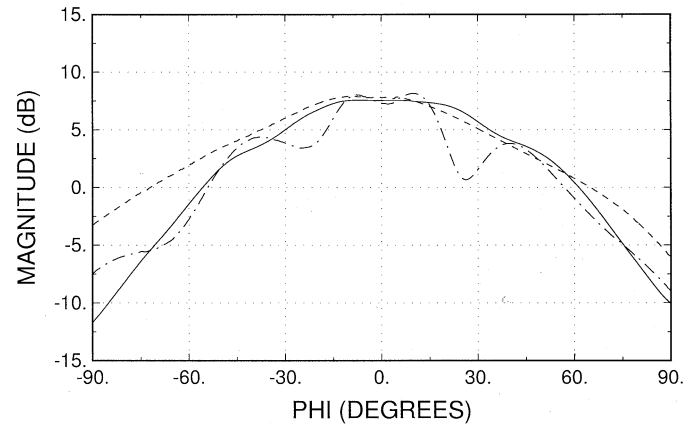


Fig. 6. Radiation pattern of element #4 of the linear array of model P-2406 antennas at 2.45 GHz. (—) measured pattern, (---) predicted pattern with identity coupling matrix, and (- · - ·) predicted pattern with calculated coupling matrix.

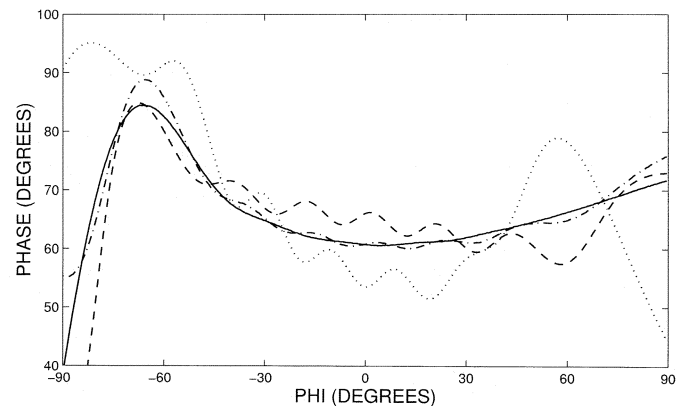
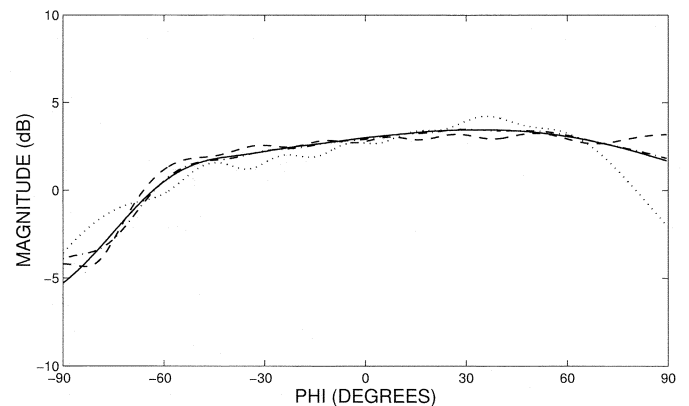


Fig. 7. Radiation pattern of element #1 of the simulated array of eight dipoles at 2.45 GHz. (—) actual pattern, (---) predicted pattern with isotropic single element, (- · - ·) predicted pattern with the single element in front of small plate, and (· · · ·) predicted pattern with the single element in front of large plate.

coupling (approximately 10 dB) between the adjacent elements, which contradicts the s_{12} measurements. The reason for the discrepancy is that when the structure scattering is dominant, then (4) does not yield the coupling matrix. Instead, \mathbf{Z} is a best fit solution. Note that even these predicted patterns do not match the measured patterns. This again emphasizes the fact that the coupling-matrix concept cannot be used to account for the structure scattering for this antenna.

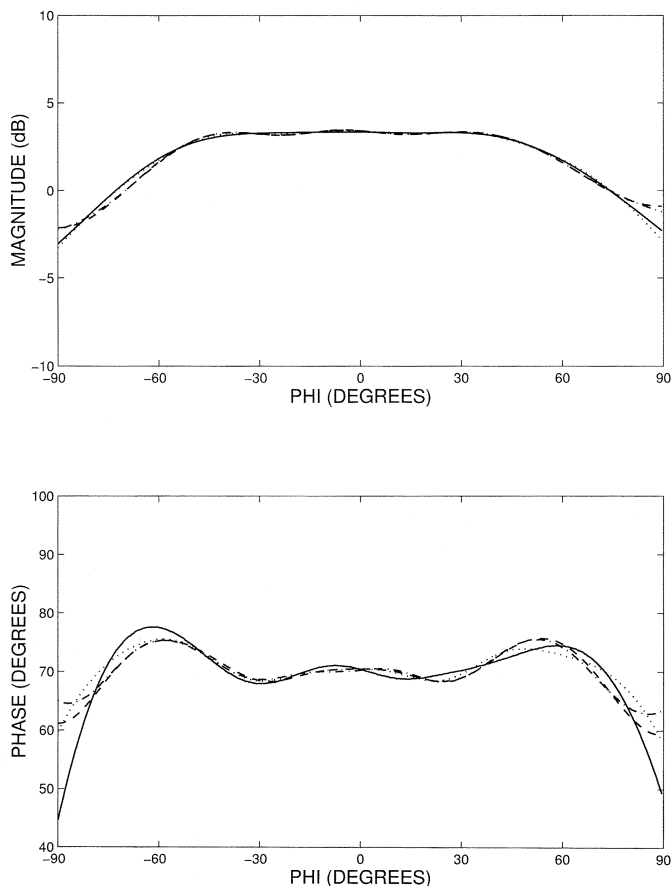


Fig. 8. Radiation pattern of element #4 of the simulated array of eight dipoles at 2.45 GHz. (—) actual pattern, (---) predicted pattern with isotropic single element, (- · - ·) predicted pattern with the single element in front of small plate, (· · · ·) predicted pattern with the single element in front of large plate.

III. NUMERICAL RESULTS

To verify the measured results, the coupling matrix approach was applied to some numerical results obtained using a MoM solution. The antenna array consisted of eight half-wavelength (6.12 cm) elements spaced 4.9 cm apart. The antennas were modeled using thin wires and ESP5 [7] was used to calculate the radiation patterns. When the antenna elements were in free space, the coupling matrix (2) worked fine. The predicted patterns matched exactly with the calculated results. Next, a perfectly conducting plate was added to the antenna array. The plate was 39.16-cm wide and 24-cm high, and was placed 3.3 cm behind the antenna array. Again, ESP5 was used to calculate the radiation patterns of the various antenna elements in this configuration at 2.45 GHz.

The continuous curves in Figs. 7 and 8 show the H plane calculated patterns for elements 1 and element 4. In these figures, magnitude as well as phase are displayed. In the phase plots, the linear component of the phase due to antenna location (away from coordinate origin) has been subtracted. Note that the radiation pattern is not uniform. This is due to the mutual coupling between various antenna elements as well as the structure scattering. As expected, the radiation patterns of different elements are somewhat different.

The other curves in these figures show the predicted patterns from (2). The broken curve is for the scenario when the radiation pattern of the single element in coupling-matrix calculation is assumed to be isotropic. The dash-dot curve is for the scenario when the radiation pattern of the single element in coupling-matrix calculation is assumed to be that of a half-wavelength dipole in front of a 4.9-cm wide \times 24-cm

high conducting plate. The spacing between the dipole and the plate is 3.3 cm. The dotted curves in the figures is for the scenario when the radiation pattern of the single element in the coupling-matrix calculation is assumed to be that of a half-wavelength dipole in front of a 39.16-cm wide \times 24-cm high conducting plate. The spacing between the dipole and the plate is 3.3 cm. To calculate the coupling matrix, 19-directions equally spaced between $-90^\circ \leq \phi \leq 90^\circ$ are used. Note that none of the predicted patterns match exactly with the calculated patterns. This is especially true for the end element (element #1). Thus, in the presence of structure scattering, one should be aware of the fact that the coupling-matrix approach may not lead to the true antenna-element patterns.

IV. SUMMARY AND CONCLUSION

The coupling-matrix concept for predicting the radiation patterns of elements of an antenna array was studied. Measured data as well as some numerical data were used in the study. It was demonstrated that in the presence of structure scattering, the coupling-matrix concept may not work very well. As expected, the stronger the structure scattering, the greater could be the discrepancy between the predicted patterns and the actual pattern. Since all antenna arrays will have some structure scattering, one should be careful in using the coupling-matrix concept for antenna-array calibration.

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