Experimental Study of Coupling Compensation of Low Profile Spiral Antenna Arrays Response for Direction-finding Applications

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Abstract **─** An experimental study of coupling compensation for AOA estimation using compact low profile antenna arrays with element separations of a quarter wavelength has been conducted. Two circular arrays of low profile miniaturised logarithmic spiral antennas deployed on a circular metal plate were used for data acquisition. Using the MUSIC direction-finding algorithm, the AOA estimation errors in receiving mode were observed before and after compensation: the errors were significantly decreased by coupling compensation.

Index Terms **─** Covariance, direction-finding, interferometry, mutual coupling.

I. INTRODUCTION

In RF covert tracking systems based on Angle-of-Arrival (AOA) estimation, compact antenna arrays with omni-directional radiation patterns are desirable [1]. However, in antenna arrays with a relatively short separation between elements, mutual coupling between the elements affects the performance of array signal processing algorithms in most cases. Mutual coupling effects are normally analysed in terms of the mutual impedances between the radiators: these have complex values, and are related to the geometrical positions of the array elements. Moreover, the mutual coupling behaviour of an antenna array in transmitting mode is demonstrably different from that in receiving mode [2, 3]. In the receiver array, when antennas receive simultaneously, the total field on each element will be the sum of the radiated and re-scattered fields from antenna elements. In radio direction-finding systems, where the directional information is obtained from the characteristic structure of the received signal matrix, mutual coupling changes the corresponding vectors of the antenna array, perturbing this correlation matrix. This results in degradation of the AOA estimation accuracy [4, 5].

To ensure accurate direction-finding, we need to address mutual coupling explicitly, and to compensate for it using a suitable decoupling method. Recently, the present authors investigated the performance of the AOA error of a 4-element uniform circular array using simple monopoles on a square metal plate in which they improved the AOA accuracy by 50% [6]. In this paper, we report an experimental study of receiving mode coupling compensation for a direction-finding application based on the Multiple Signal Classification (MUSIC) algorithm using four and six-element uniform circular arrays of spiral antennas.

II. LOW PROFILE SPIRAL ANTENNA ARRAY

To examine the performance of arrays in receiving mode using compensation, two networks, with either four or six-elements, using low profile miniaturised logarithmic spiral antennas were designed. Each antenna provides a monopole-like radiation pattern and supports platform installations at TETRA/UHF frequencies [7].

The antenna prototype with its measured radiation pattern is shown in Fig. 1. It should be noted that the radiation pattern for the designed prototype antenna was considered at its resonant frequency and it is assumed that the radiation performance will be in agreement for all the elements at their resonances frequencies over all working frequency bands. Prototypes were fabricated and installed on circular ground planes of diameter one meter, as shown in Fig. 2. The inter-element spacing is set to a quarter wavelength and the radii of the four and six-element circular arrays are 0.1325 and 0.1595 meters respectively. The measured return losses of all the prototypes over the desired frequency band (420 MHz to

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425 MHz) are shown in Fig. 3. The minor dissimilarity in the frequency responses is due to the mismatches in hardware designs of the elements. The measured array response acquired in the array calibration process and used in the MUSIC algorithm includes these mismatches, but the final estimated AOA results are not significantly affected.

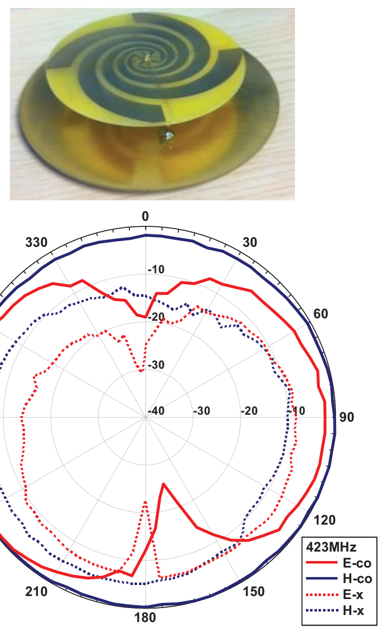
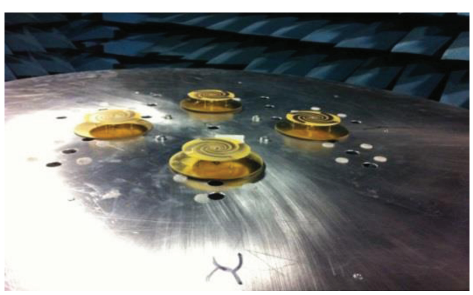
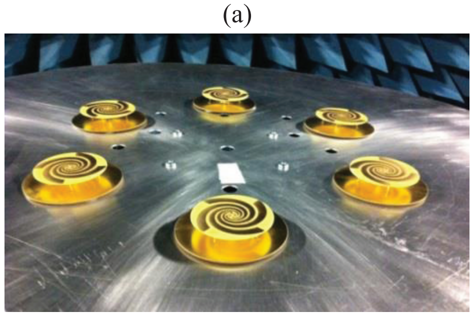


Fig. 1. Multi-element low profile spiral antenna prototype and its measured radiation pattern in principal E-plane and H-plane co-polarization and cross-polarization.



(a)



(b)

Fig. 2. Antenna array geometries used for data acquisition.

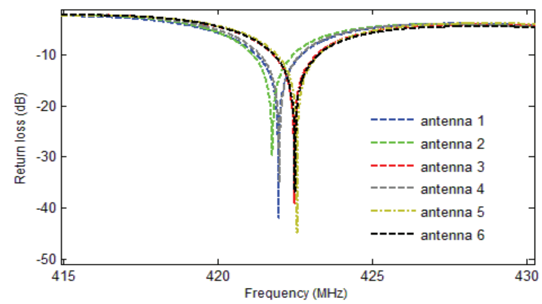


Fig. 3. Measured return losses of low profile spiral antennas

III. RECEIVING MUTUAL IMPEDANCES USING S-PARAMETER MEASUREMENT

The mutual impedance is calculated under the conditions that the antenna elements are terminated with known impedance, Z_L and that they are in receiving mode under an external plane-wave excitation [2, 3, and 8]. Consider an antenna array with N antenna elements, each of which is terminated with an identical load impedance, Z_L. When the array is excited by an external source, the voltage at antenna terminal V_k can be written as:

$$V_k = Z_L I_k = U_k + W_k, \tag{1}$$

where $\boldsymbol{U_k}$ is the terminal voltage due solely to the direct incoming signal and $\boldsymbol{W_k}$ is the voltage due to the mutual coupling with other antenna elements. $\boldsymbol{W_k}$ can be written as:

$$W_k = I_1 Z_t^{k,1} + I_2 Z_t^{k,2} + \cdots + I_{k-1} Z_t^{k,k-1} + I_{k+1} Z_t^{k,k+1} + \cdots + I_N Z_t^{k,N}, \tag{2}$$

where $\boldsymbol{Z_t^{k,i}}$ is the receiving mutual impedance between antenna elements k and i, and I_i is the current induced at the terminal of antenna element i. The subscript t denotes that the receiving mutual impedance is defined at the antenna's terminals. The relationship between $\boldsymbol{U_k}$ and $\boldsymbol{V_k}$ can be written as:

$$\begin{bmatrix} 1 & -\frac{Z_t^{12}}{Z_L} & \cdots & -\frac{Z_t^{1N}}{Z_L} \\ -\frac{Z_t^{21}}{Z_L} & 1 & \cdots & -\frac{Z_t^{2N}}{Z_L} \\ \vdots & \vdots & \ddots & \vdots \\ -\frac{Z_t^{N1}}{Z_L} & -\frac{Z_t^{N2}}{Z_L} & \cdots & 1 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} U_1 \\ U_2 \\ \vdots \\ U_N \end{bmatrix}. \tag{3}$$

Using Equations (1) and (2), determination of the receiving mutual impedances is based on terminal currents or voltages. Since the miniaturised logarithmic spiral antenna has an omni-directional radiation pattern, it is assumed that the current distribution remains unchanged irrespective of the azimuth angle of the incoming signal when the signal is coming from the plane perpendicular to the axis of the antenna (θ=90°). As a result, the receiving mutual impedance should remain constant with respect to the azimuth angle of the incoming signal, and thus is suitable for direction-of-arrival estimation applications [2].

In order to obtain mutual impedances, two elements of the array at a time should be considered, with the remaining elements loaded. The following steps are repeated to retrieve the corresponding S_{12} parameters:

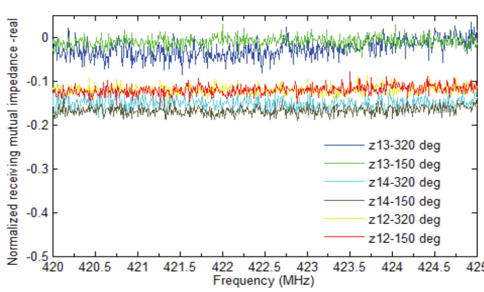
(1) Measure S_{12} at element 1's terminal with element 2's terminal connected to a load. Denote this as S_{12_1};
(2) Measure S_{12} at element 2's terminal with element 1's terminal connected to a load. Denote this as S_{12_2};
(3) Measure S_{12} at element 1's terminal with element 2 removed from the array. Denote this as S'_{12_1};
(4) Measure S_{12} at element 2's terminal with element 1 removed from the array. Denote this as S'_{12_2}.

Accordingly the receiving mutual impedances can be obtained as follows:

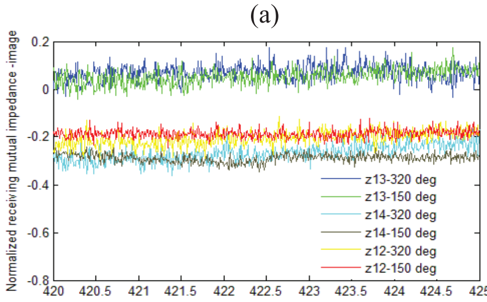
$$Z_t^{12} = \frac{S_{12\_1} - S'_{12\_1}}{S_{12\_2}} Z_0, \quad (4)$$

$$Z_t^{21} = \frac{S_{12\_2} - S'_{12\_2}}{S_{12\_1}} Z_0. \quad (5)$$

The above procedure needs to be repeated for all pairs of elements in an array. Figure 4 shows calculated mutual impedances between the first antenna and the rest of the radiators, both (a) real and (b) imaginary parts, using the measured S-parameters for a 4-element array. In this example, signals are arriving from 150 and 320 degrees. These two angles are chosen to illustrate cases where the measured array responses in the azimuth plane without coupling compensation give rise to considerable angular errors.



(a)



(b)

Fig. 4. Normalized mutual impedance for AOA = 150 and 320 degrees over the frequency band: (a) real part and (b) imaginary part.

In order to obtain the compensation matrix in Equation (3), mutual impedances for pairs of antennas are determined for many directions which show considerable angular errors in the measured array response in the azimuth plane. It is clear from the graphs in Fig. 4, that the variation of the mutual impedances over the 5 MHz of bandwidth is negligible, and thus narrowband compensation would be sufficient. Thus, the mutual impedances are averaged from 420 MHz to 425 MHz and over different angles. The mutual coupling values for both array geometries are listed in Tables 1 and 2.

IV. AOA ESTIMATION RESULTS

Deriving mutual coupling compensation entails developing an estimate for the actual array response for the specified geometries via the results from Tables 1 and 2. The resultant vectors must subsequently be applied to the MUSIC algorithm for direction-finding. In this study, in order to capture the array response to signals coming from different azimuth angles, the data acquisition setup shown in Fig. 5 was used. Log-periodic antennas have been used as transmitters to create the plane wave source in an anechoic chamber. To send data from each terminal in turn to the network analyser, a microwave switch has been deployed under the turntable while the dc controller of the switch was located outside the chamber. The amplitude and phase responses from each antenna have been captured for rays from the azimuth plane and post-processed using the compensation matrices and AOA estimation algorithm. Figures 6 and 7 show the spatial spectra generated using uncompensated and compensated array responses for measurement data due to pairs of signal sources to the four and six-element spiral arrays, respectively.

When the measured voltages are used without any compensation for mutual coupling for the four-element array, Fig. 6 shows that although the MUSIC spatial spectrum function shows two peaks, the peaks are not adequately sharp and also are misplaced by about 20 and 40 degrees for the signals coming from 30 and 150 degree azimuth angles, respectively.

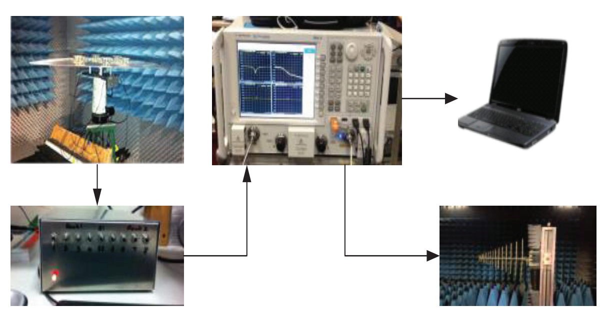


Fig. 5. Data acquisition setup for the AOA estimation experiment.

Table 1: Normalized receiving mutual impedances for a 4-element spiral array

Var.	Value	Var.	Value
Z_t^{12}	-0.126 - 0.213i	Z_t^{31}	0.098 + 0.171i
Z_t^{13}	-0.019 + 0.089i	Z_t^{32}	0.139 - 0.307i
Z_t^{14}	-0.184 - 0.234i	Z_t^{34}	0.288 - 0.085i
Z_t^{21}	0.054 + 0.192i	Z_t^{41}	-0.114 + 0.079i
Z_t^{23}	0.164 - 0.170i	Z_t^{42}	0.203 - 0.006i
Z_t^{24}	0.169 + 0.334i	Z_t^{43}	0.176 - 0.113i

Table 2: Normalized receiving mutual impedances for a 6-element spiral array

Var.	Value	Var.	Value
Z_t^{12}	-0.540 + 0.089i	Z_t^{41}	-0.135 - 0.236i
Z_t^{13}	0.054 - 0.651i	Z_t^{42}	0.220 - 0.335i
Z_t^{14}	0.025 - 1.067i	Z_t^{43}	0.461 + 0.143i
Z_t^{15}	-0.488 - 0.028i	Z_t^{45}	0.336 - 0.229i
Z_t^{16}	0.173 + 0.444i	Z_t^{46}	-0.182 - 0.100i
Z_t^{21}	0.220 + 0.044i	Z_t^{51}	0.066 + 0.100i
Z_t^{23}	-0.290 - 0.364i	Z_t^{52}	-0.085 + 0.171i
Z_t^{24}	0.092 - 0.227i	Z_t^{53}	-0.333 - 0.246i
Z_t^{25}	0.048 + 0.150i	Z_t^{54}	0.456 - 0.470i
Z_t^{26}	0.210 + 0.103i	Z_t^{56}	0.342 + 0.108i
Z_t^{31}	0.164 - 0.142i	Z_t^{61}	0.225 + 0.221i
Z_t^{32}	0.307 + 0.090i	Z_t^{62}	-0.326 + 0.108i
Z_t^{34}	0.014 + 0.385i	Z_t^{63}	0.163 - 0.334i
Z_t^{35}	0.269 + 0.024i	Z_t^{64}	-0.136 - 0.610i
Z_t^{36}	0.058 - 0.313i	Z_t^{65}	-0.158 + 0.001i

However, applying the receiving mode compensation matrix from Table 1 to these results provides sharper peaks and reduces the AOA estimation error to less than ± 2 degrees. In the second experiment, two incident waves irradiate the six-element spiral array from 40 and 110 degree azimuth angles. As shown in Fig. 7, applying the receiving mode compensation matrix using data from Table 2 results in an AOA estimation accuracy of about ± 1 degree for the two directions.

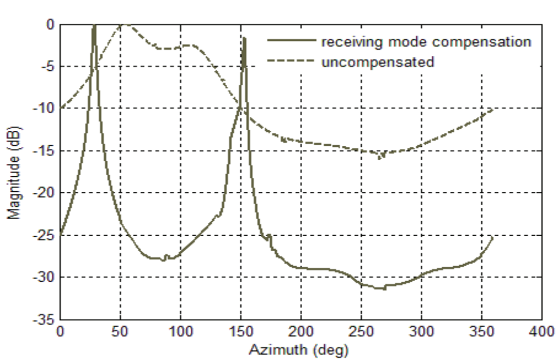


Fig. 6. MUSIC spatial spectrum for two incident signals with azimuth angles of 30 and 150 degrees, four-element low profile spiral array.

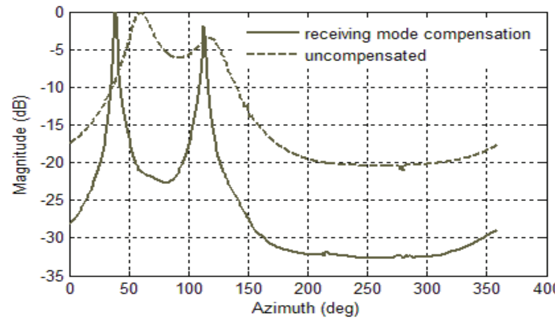


Fig. 7. MUSIC spatial spectrum for two incident signals with azimuth angles of 40 and 110 degrees, six-element low profile spiral array.

V. CONCLUSION

In this experimental study, the benefit of mutual coupling compensation during AOA estimation process using low profile spiral antenna arrays has been examined. The receiving mode compensation matrices were derived by numerical calculations using measured data from four and six-element arrays. It was shown that over the 5 MHz bandwidth the mutual impedances do not vary significantly, and thus narrowband compensation would be sufficient. Moreover, since the low profile spiral antenna has an omni-directional radiation pattern, the compensation matrix is independent of angle. The marked performance improvement in terms of AOA estimation, due to the compensated array responses, allows for easier and more accurate determination of multiple signal sources.

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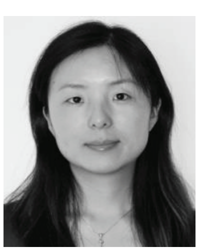

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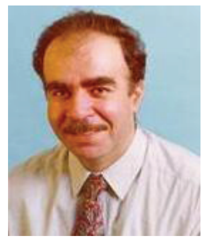

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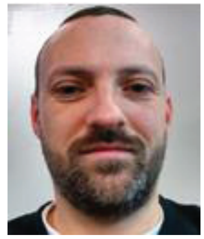

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